March 1987

ANL-SAFR-37
ANL-PRISM-41

AIR-SIDE PERFORMANCE OF RVACS/RACS--DESCRIPTION OF THE NATURAL CONVECTION SHUTDOWN HEAT REMOVAL TEST FACILITY AND SUPPORTING ANALYSIS

by

T. T. Anderson, C. August, N. J. Carson, O. D. Despe, H. J. Haupt, J. B. Heineman, M. R. Kraimer, P. A. Lottes, H. J. Myers, J. R. Pavlik, D. R. Pedersen, G. J. Pokorny, R. R. Stewart, and J. H. Tessier

Reactor Analysis and Safety Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AIR-SIDE PERFORMANCE OF RVACS/RACS--DESCRIPTION OF THE NATURAL CONVECTION SHUTDOWN HEAT REMOVAL TEST FACILITY AND SUPPORTING ANALYSIS

by

T. T. Anderson, C. August, N. J. Carson, O. D. Despe, H. J. Haupt, J. B. Heineman, M. R. Kraimer, P. A. Lottes, H. J. Myers, J. R. Pavlik, D. R. Pedersen, G. J. Pokorny, R. R. Stewart, and J. H. Tessier

ABSTRACT

This report contains a description of the construction/fabrication status of the Natural Convection Shutdown Heat Removal Test Facility as of July 1986 and the concomittant pre-test analysis for the PRISM/RVACS (Radiant Vessel Auxiliary Cooling System) configuration installed for the initial experiments. Also included is the initial test plan and contingent test phases. The current schedule anticipates initial power operations in late October. (Since this report was issued in draft form in July, construction has been completed and experiment operations began in November 1986).

1.0 AIR-SIDE TEST FACILITY

This section describes the current status of the ANL out-of-pile experiment test assembly that simulates the GE Radiant Vessel Auxiliary Cooling System (RVACS). This description is an update of the design and fabrication/assembly status presented in reference 1.

The RVACS air-side experiments will be carried out at ANL in Building 310, a facility which provides the required high-bay capability for the full-scale simulation of the guard vessel/collector geometries typical of LMR pool-type designs. Figure 1 is an aerial view of the ANL "300" area, looking northeast. Indicated is the location of Building 310 and also shown is the location of externals pertinent to RVACS, i.e., the exhaust (hot-air) stack, and the meteorological tower. Neither is in place to date.

The Test Assembly is comprised of a structural model, electric heaters, instrumentation, insulation, and a computerized control and data acquisition system. Experiment operation will simulate prototypic reactor vessel temperatures, air flow patterns, and heat removal conditions that would exist for a RVACS system during normal reactor operation and/or a shutdown situation. In general, the system will operate in either of two thermal modes: (1) constant guard vessel wall temperature to 1000°F or (2) constant heat flux to 2.0 kW/ft^2. In addition, the system will accommodate stepwise variation of either mode singly or in combination.

1.1 Segment Test - Mechanical Systems

Figure 2 illustrates the basic assembly configuration and salient features. A major design change for more prototypic stack effect has been incorporated as shown, i.e., addition of an "S" section and a vertical run and weather cap to approximately 50 ft. above the previous design of the air flow exit (see reference 1). Figures 3 and 4 show the current status of test assembly mechanical design, fabrication, procurement, and in-place assembly.

Major activities completed in the past several months are as follows:

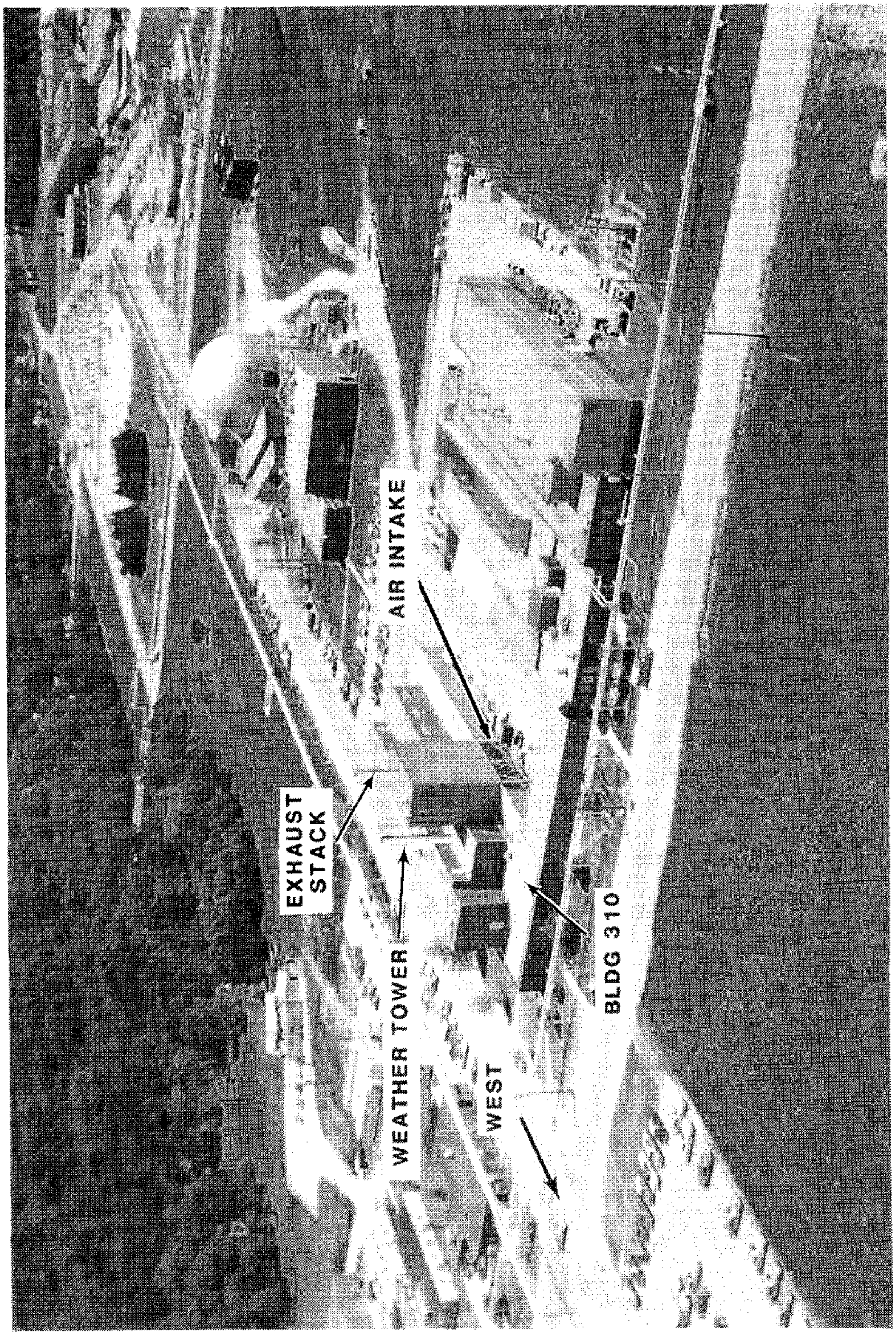


Figure 1. Aerial View - Building 310 Area

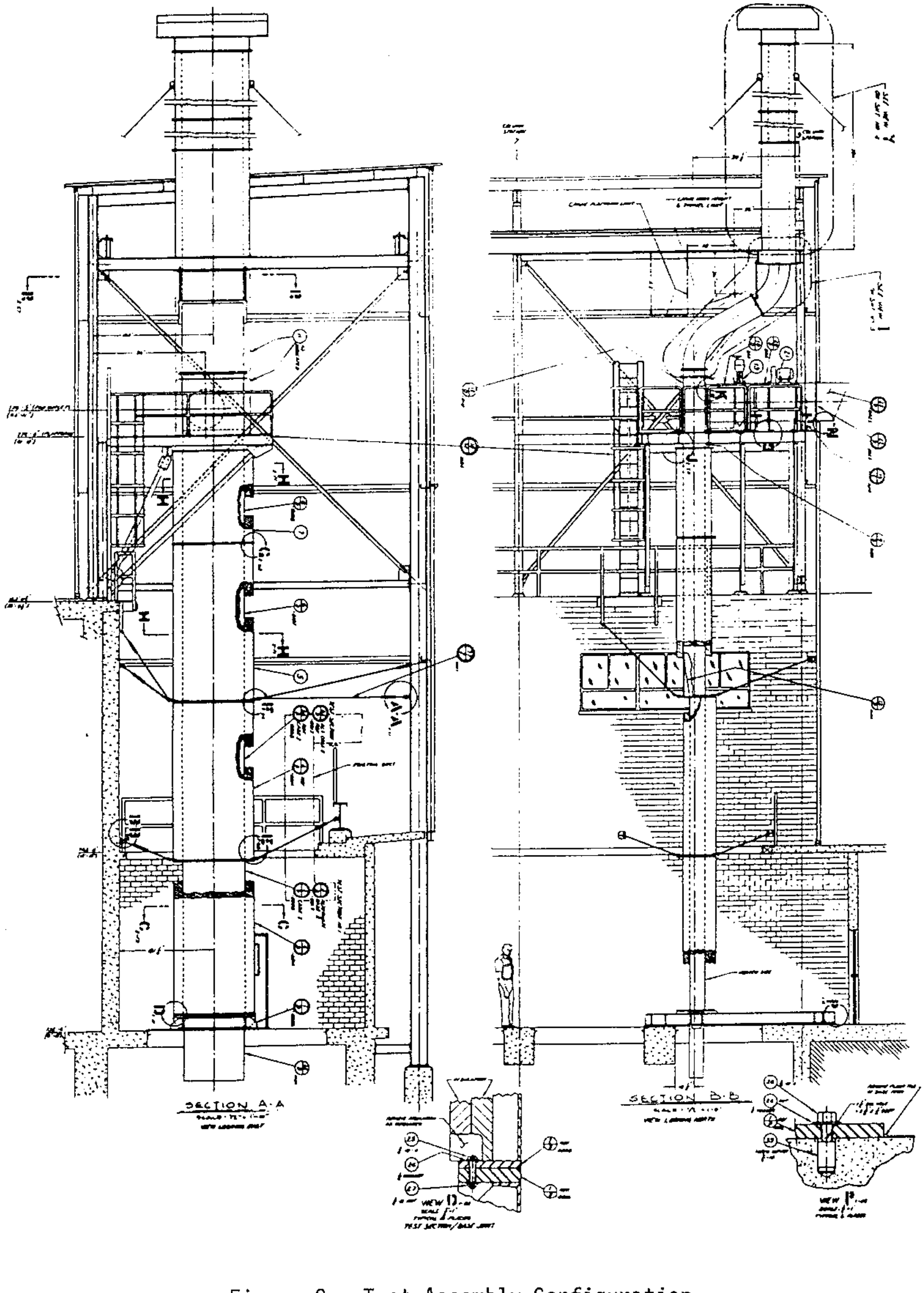
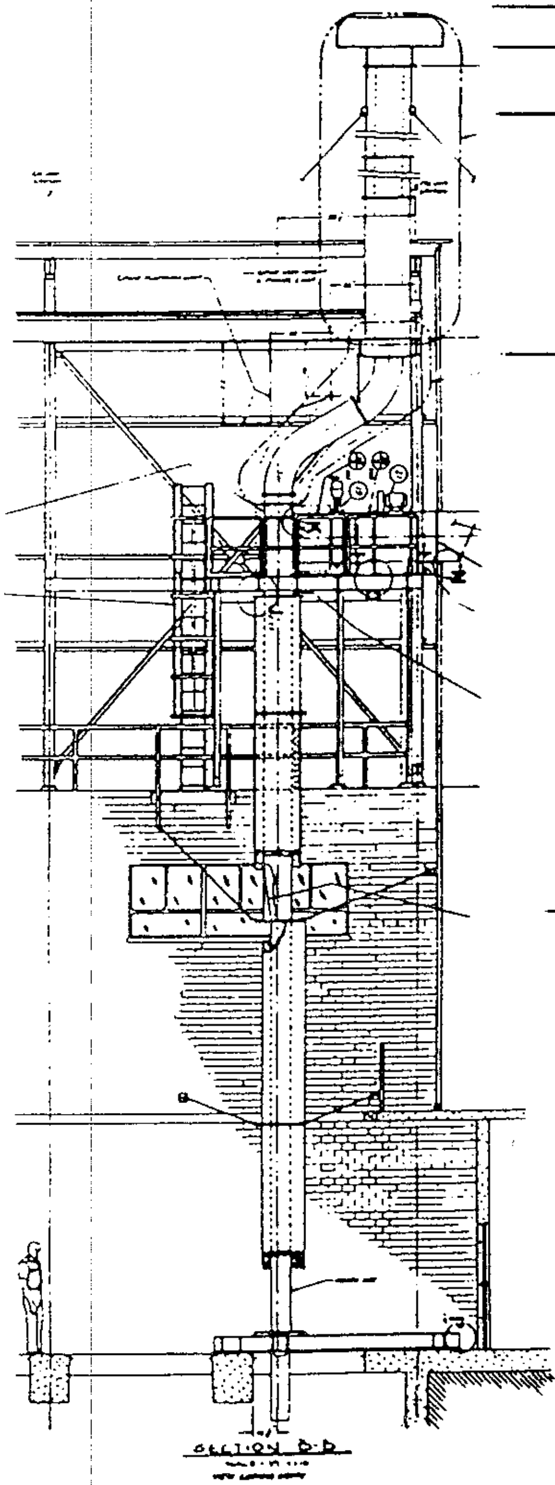


Figure 2. Test Assembly Configuration

7/25/86



COMPONENT	STATUS
Weather Cap	final Design
Thermocouple Assy	in Design
Exhaust Stack (Natural Circulation)	at Procurement
Fan & Damper Ductwork Components	Complete
Test Sections	Complete
Base	Complete
Inlet	at Procurement

Figure 3. Mechanical Design and Fabrication Status

ANL Building 310 7/25/86

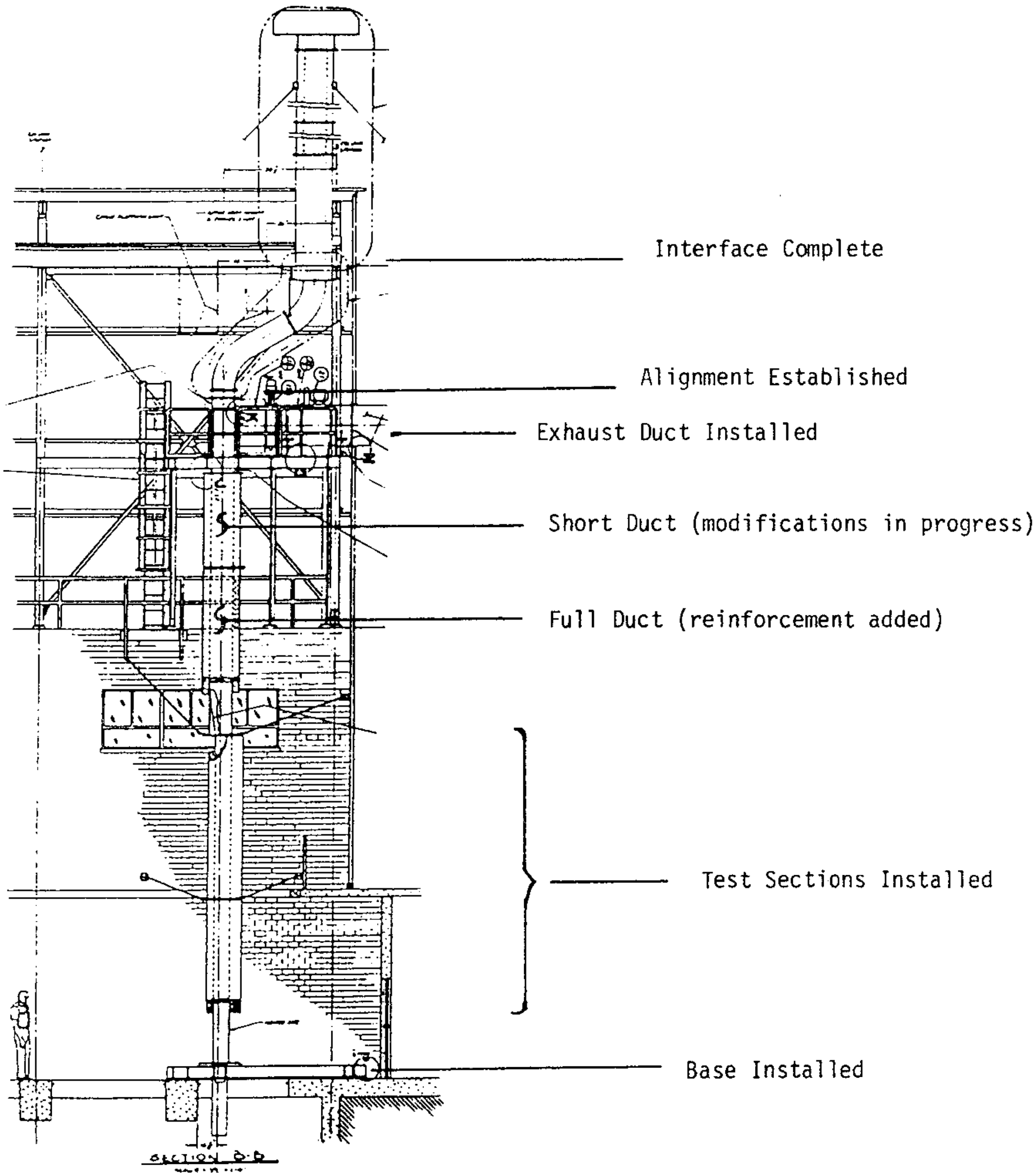


Figure 4. Mechanical Assembly Status

- Service platform installed.
- Forced circulation fan and damper procured.
- Support base fabricated and installed.
- 2-part test section fabricated and installed, thermocouples attached.
- Ductwork between test section and exhaust stack fabricated.

Mechanical activities in progress include:

- Final mechanical assembly drawings.
- Pitot/temperature traverse mechanism support development.
- Procurement of exhaust fan, stack ductwork, weather cap, weather tower.
- Exhaust stack thermocouple assembly design and fabrication.

Figure 5 shows the two 11 ft. vertical test section modules in place with the attached thermocouple leads. Figure 6 is a view of the upper 11 ft. section, showing the side plates and insulation (between side plates and the heated plate) from the heated plate (back side).

1.2 Electrical Systems

1.2.1 Heater System

The heater system design as shown in Figure 7 is not different from that shown in reference 1. Heater resistances have been measured to provide input data for on-line calculation of "local" power (heat flux) during experiments (E^2/R x SCR on-time). Figure 8 shows a typical heater "zone" ready for assembly to the test section. There are 5 heater

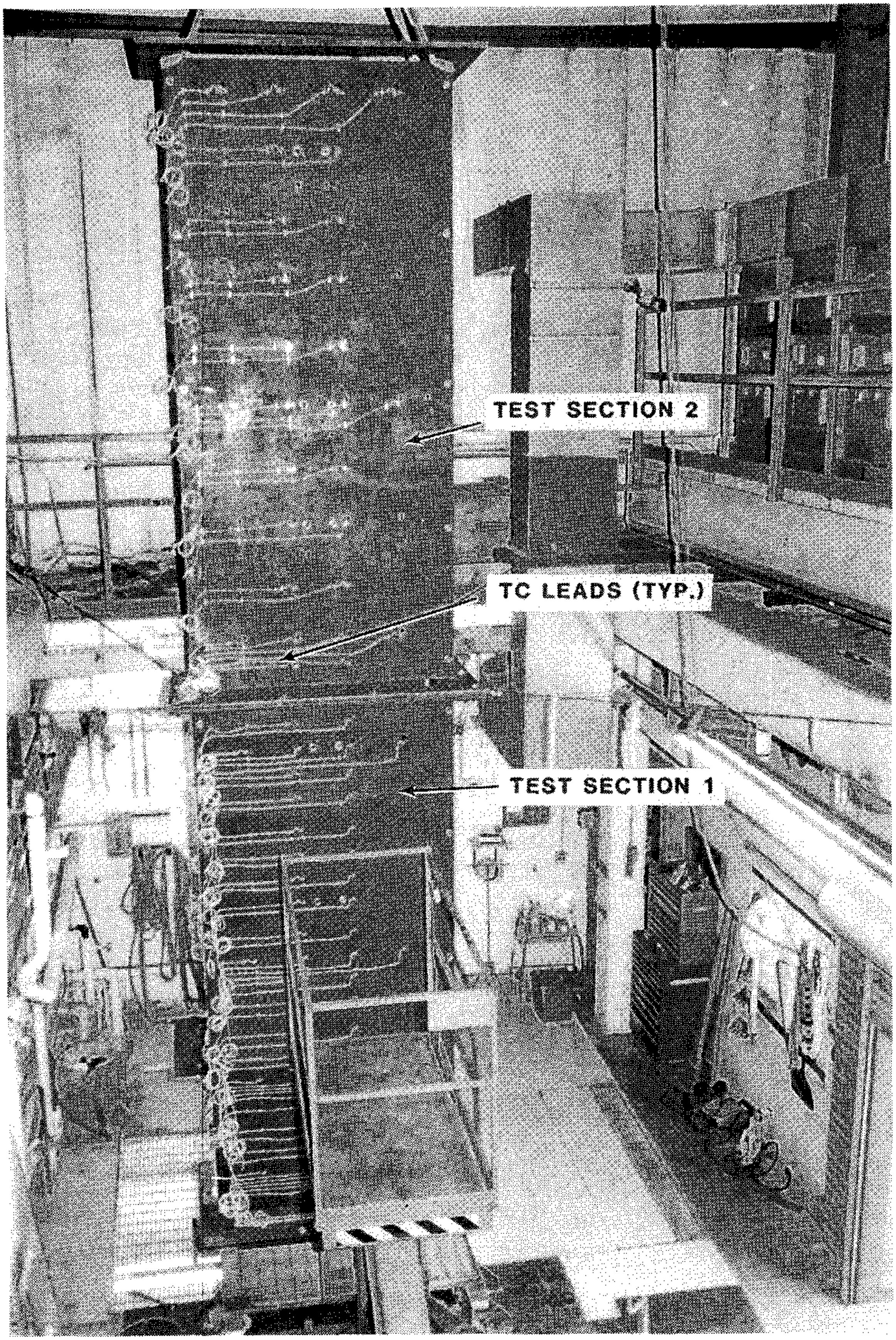


Figure 5. Test Section in Place

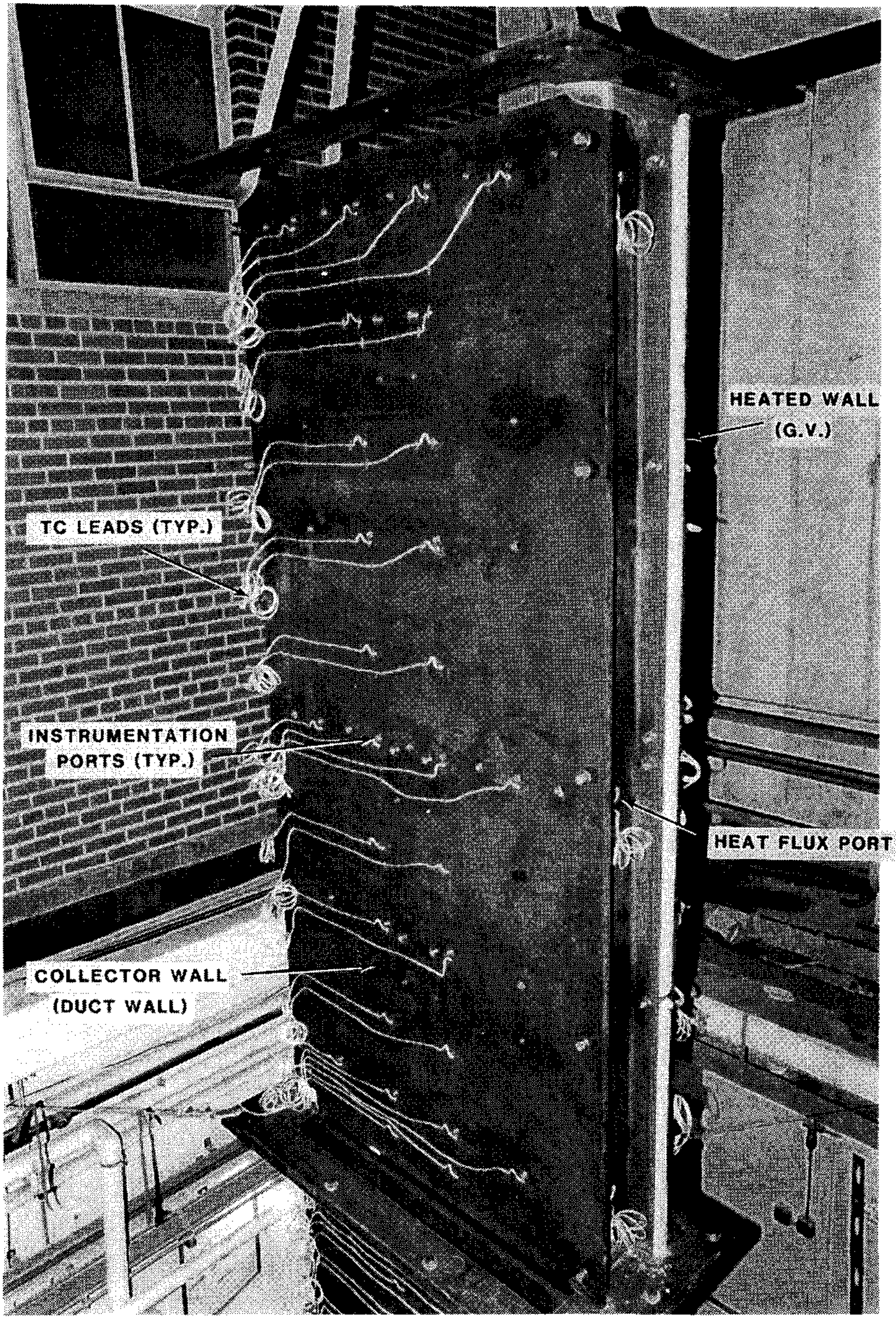


Figure 6. Upper Test Section in Place

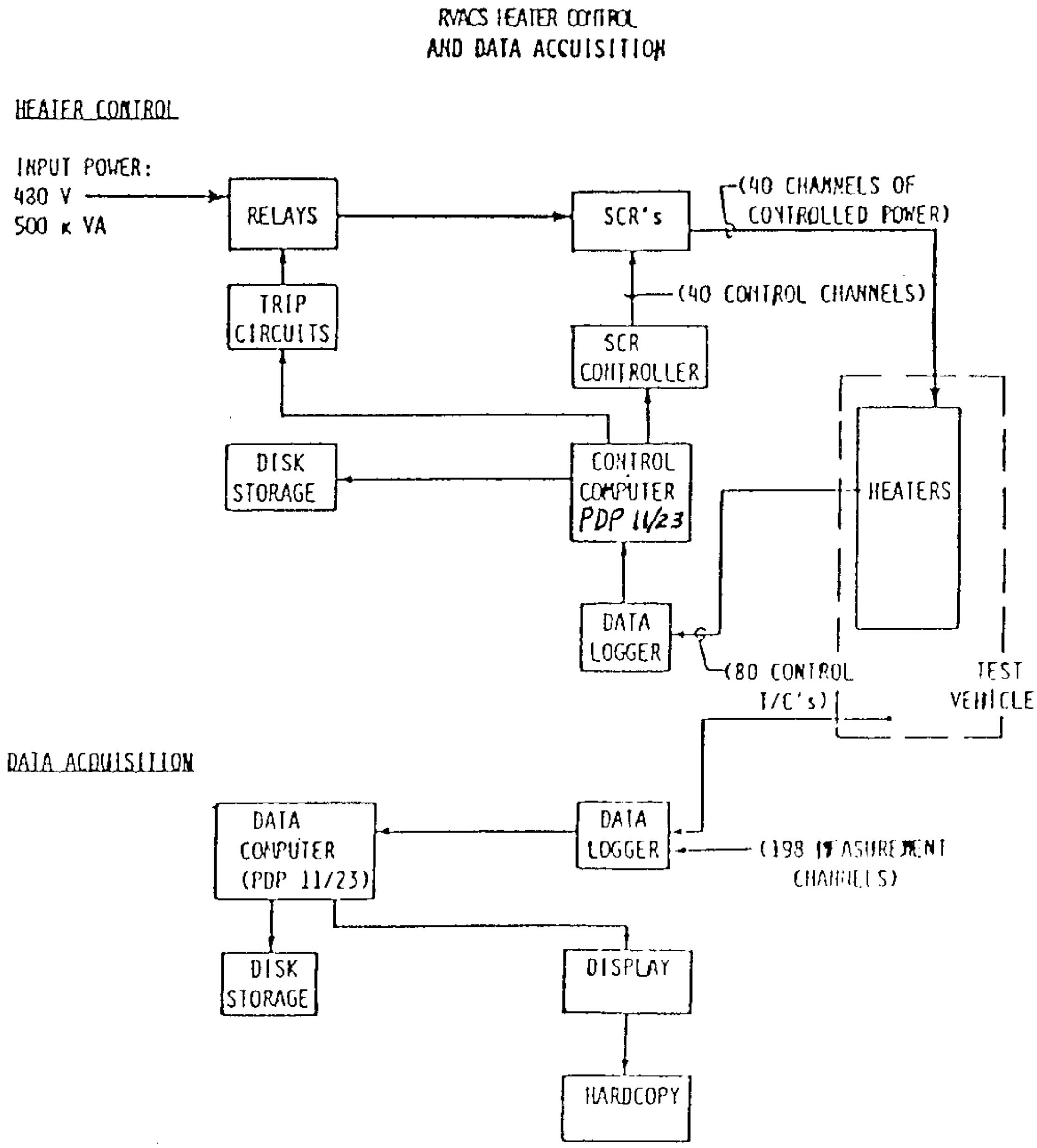


Figure 7. RVACS Heater Control and DAS System

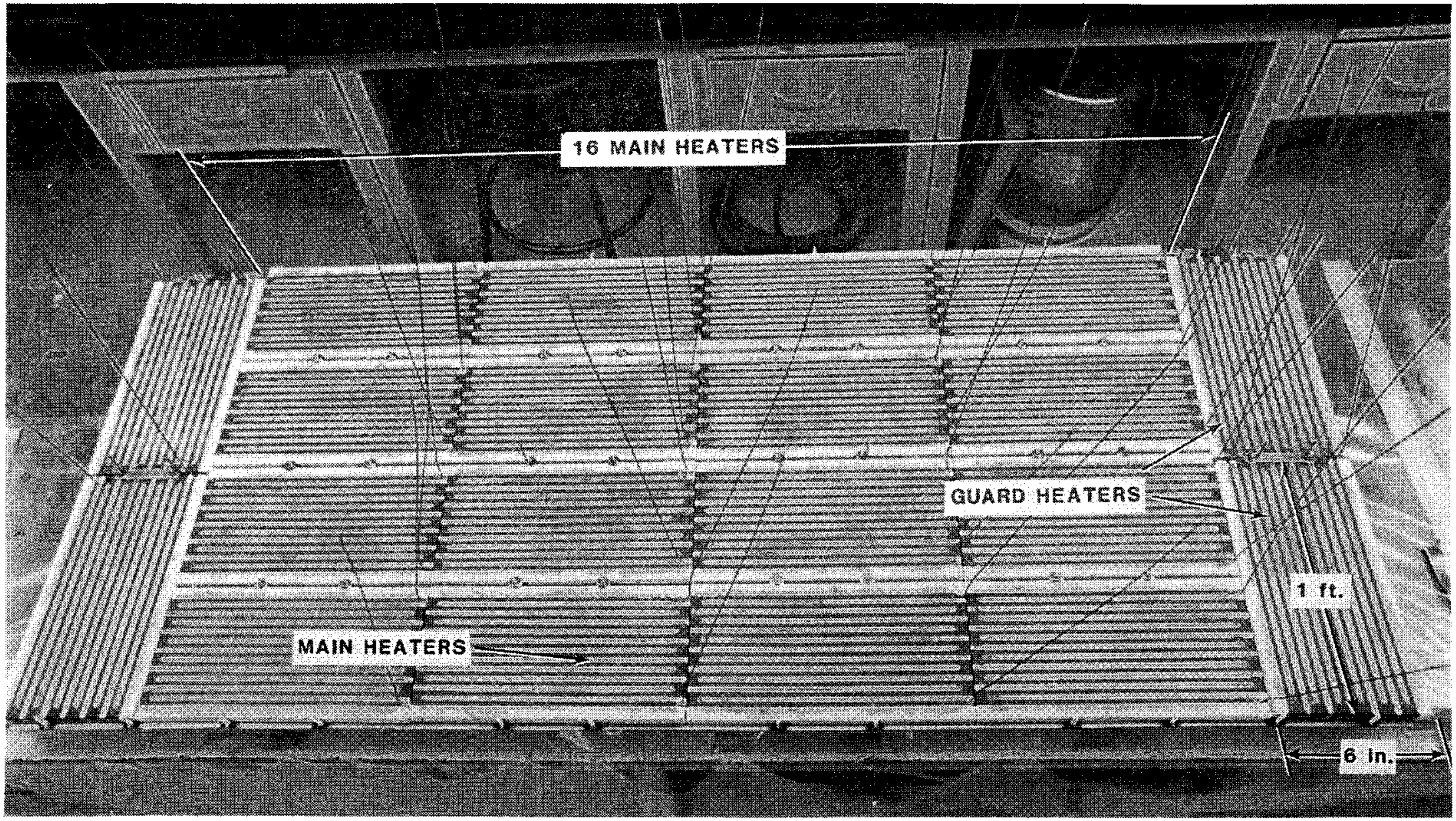


Figure 8. Typical Heater Section

plate zones per 11 foot test section, each with individual heater control (including guard heaters). The center 16 heaters on the heater plate represent one heater zone with the four edge heaters being guard heaters. This array of 20 plate heaters represents 10% of the total heated length in the 22 foot test arrangement. Figure 9 is a closeup picture showing details of the heater leads and the control thermocouple locating studs.

These heaters are designed to operate at 120 V each in strings of four (in Figure 8, the heaters will be wired in series-parallel for 480 V operation). The design limit of the heaters is 2200°F and 1/2 kW. This is substantially more power than required for testing; the heater temperature will be controlled and limited to 1600°F operation. The 440 V power supply and buses are in the installation phase.

1.2.2 Auxiliary and Instrument Power

In addition to heater power, several system components require 110 V service:

- Service power (lighting, etc.).
- Variable speed, reversible fan and damper control power.
- Control console and instrument power (Figures 10 and 11).
- On-line computers/DAS systems (Figures 10 and 11).

The service power and fan/damper power are in the installation phase.

Assembly of the control console is essentially complete, as shown in Table I. Final system checkout will occur when all sensor/transducer connections are complete.

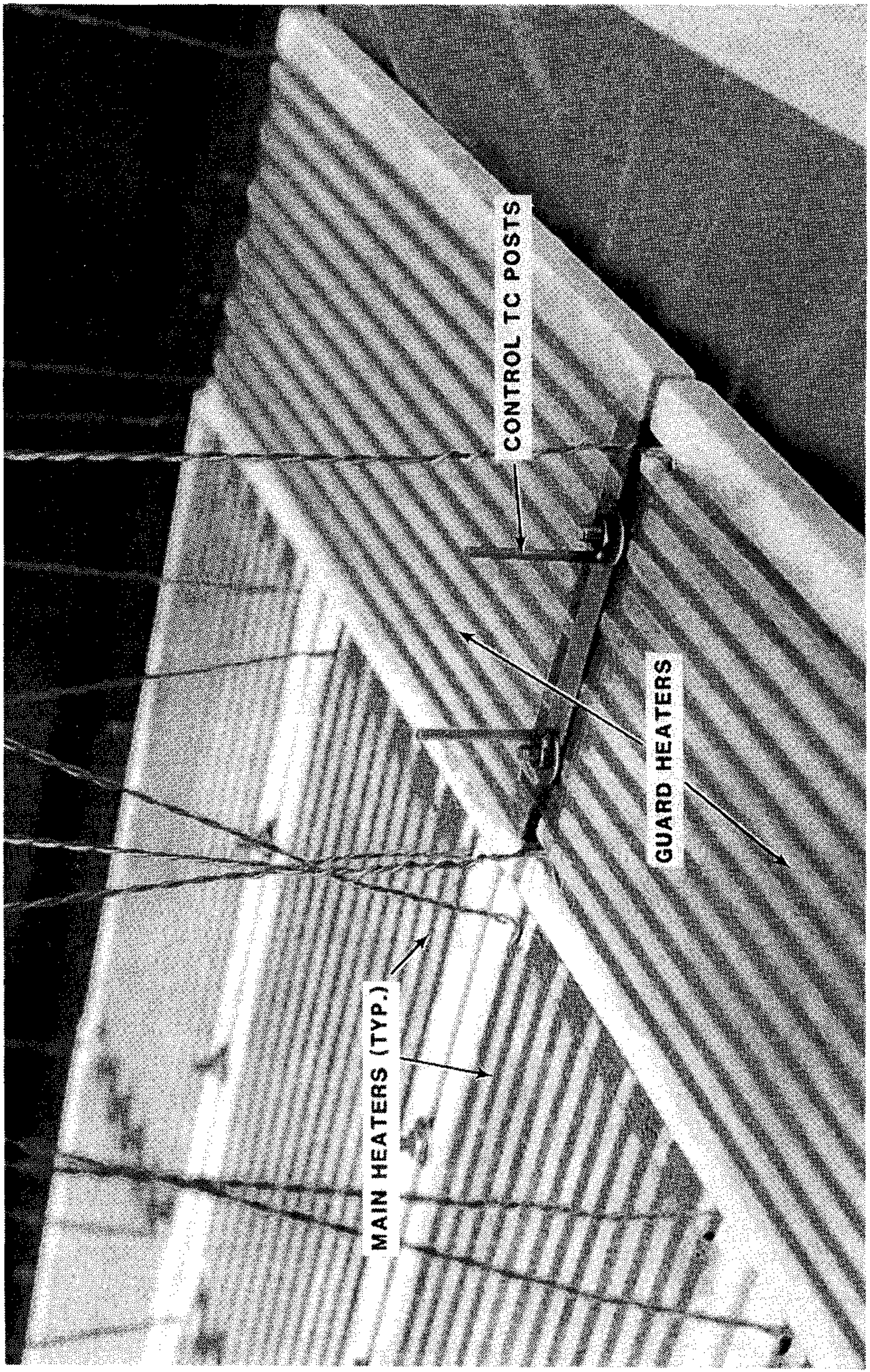


Figure 9. Heater Detail

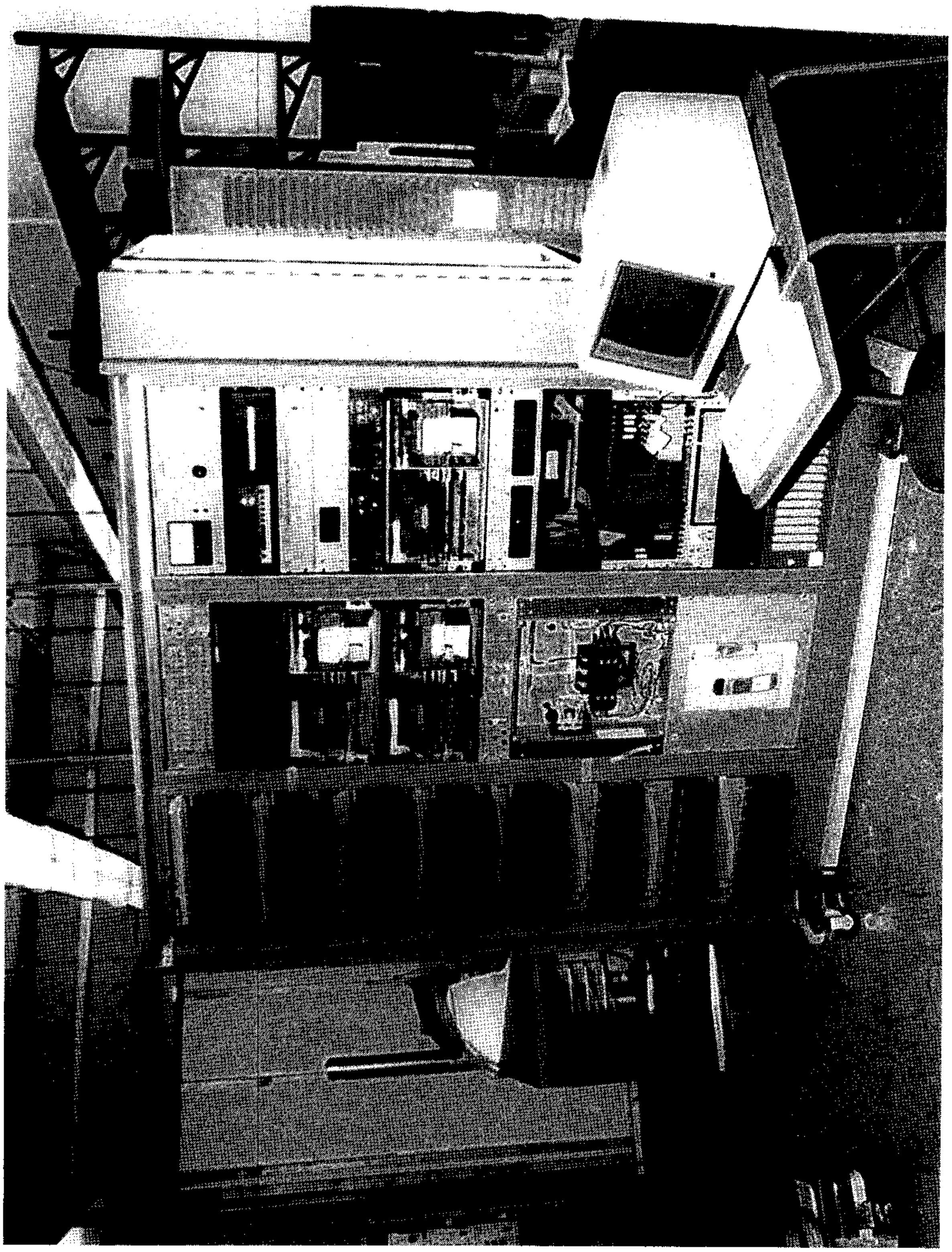


Figure 10. RVACS Console

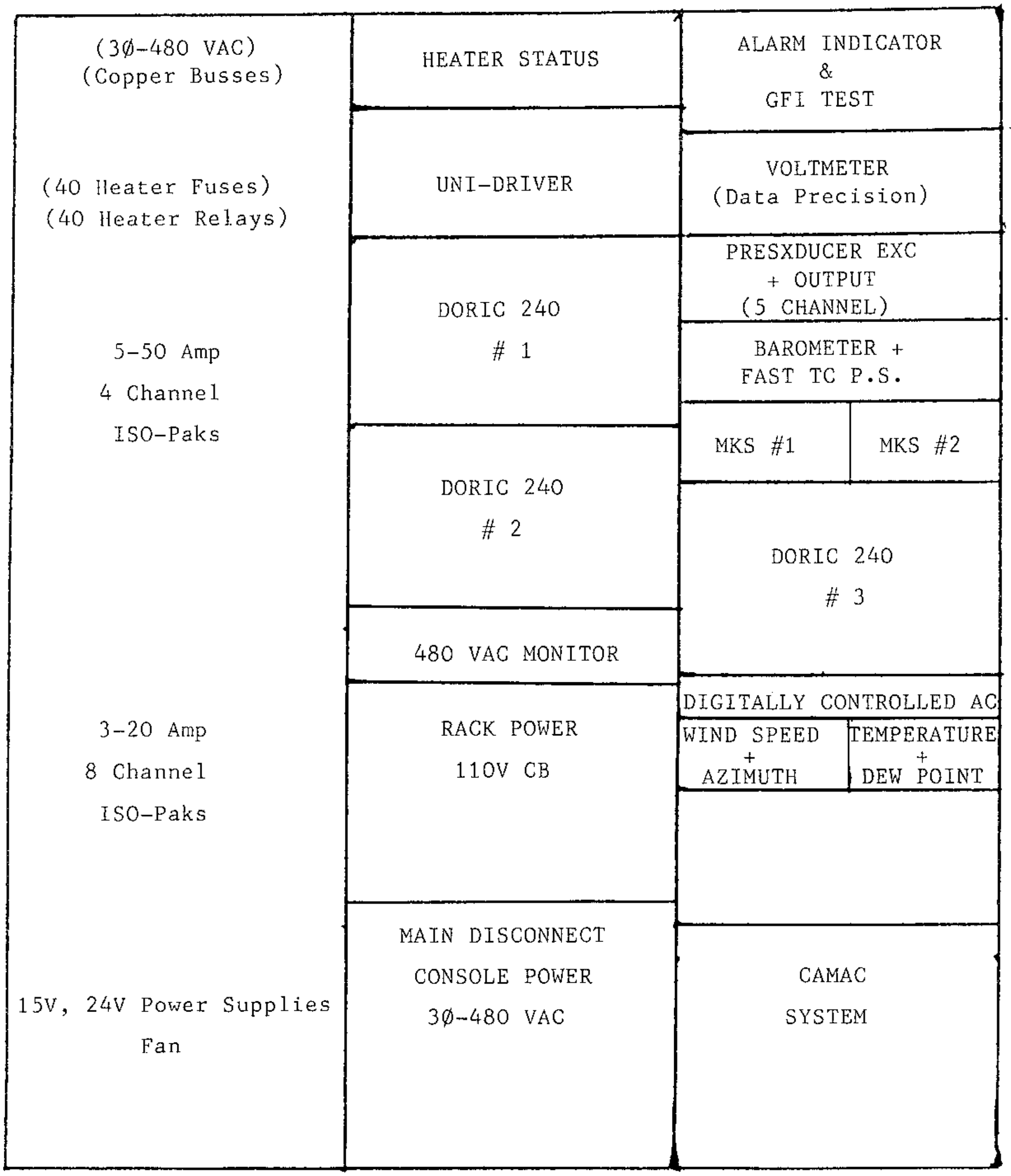


Figure 11. RVACS Console Configuration

Table I. Control Console Status

RVACS Control Console	
Custom/Semicustom Subsystem	Status
Alarm Indicator Chassis	Complete
Ground Fault Interrupt GFI	Complete*
Heater Status and Contractor Drive	Complete
480 VAC 30 main & Console Monitors	Complete
5-Channel Pressure Monitor	Complete
8-Channel Digitally Controlled 110 VAC	Complete
Barometer & Fast TC Inputs	Complete
Access Panel (TC's & Voltage Inputs)	Complete
Traversing Mechanism Driver Interface	Complete
Commercial Subsystems	
2 Mks (Baratron) Units Measurement System & Interface	Complete
Unidriver/CAMAC Interface	Complete
3-100 Channel DORIC 240	Complete
Wind and Azimuth System	Complete*
Temperature & Dew Point Unit	Complete*
Console Power System	
3Ø 480 VAC Power Circuit (Left Bay)	Complete
- Main 3Ø Copper Buses	Complete
- Heater Fuse Blocks	Complete
- Heater Relays (contractors)	Complete
- Iso-Paks/Unidriver	Complete
3Ø 110 VAC Console Instruments/Control Power	Complete
- 15 kW 3Ø 480V/120V Transformer	Complete
- 3Ø Fused Disconnect Switch	Complete
- 6-20A Load Circuit Breakers	Complete

*Not completely checked out.

1.3 Instrumentation

The instrumentation requirements (Table II) have been revised to reflect some changes in secondary experiment objectives and test planning. The status of instrumentation is as follows:

- All of the thermocouples for the heated wall and the duct wall have been installed.

- The 10 radiation shielded TC assemblies, pitot tubes, and the radiation sensors are in procurement.

- The outlet air flow sensor, the stationary pressure sensors, and the heater AC instruments are ready for installation and/or connection to the DAS/control systems.

- A meteorological tower will be installed on the building to measure wind direction, velocity and temperature.

1.4 Data Acquisition System (DAS)

The DAS/heater control system block diagram is shown in Figure 12. A considerable amount of detailed software effort has been completed (naming variables, etc.). The following description is an overview of the DAS/heater control status.

1.4.1 DAS Operations

At periodic intervals the following parameters are recorded:

- All sensors connected to the Doric data loggers.

- Unidriver settings.

- Power input to each heater.

Table II. Instrumentation Requirements - RVACS

INSTRUMENTATION DESCRIPTION	MINIMUM REQUIRED VALUES			
	QUANTITY[1]	RANGE	ACCURACY[2]	RESPONSE[3]
THERMOCOUPLES				
Heater Overtemperature	2 per heater circuit	0 to 1900°F	± 4°F or ± 0.75%	30 sec
Guard Vessel	2 per heater circuit and 2 per 2 ft elevation of test section	0 to 1300°F	± 4°F or ± 0.75%	30 sec
Duct Wall	2 per 2 ft elevation of test section	0 to 900°F	± 4°F or ± 0.75%	30 sec
Side Wall	2 per 4 ft elevation of test section	0 to 900°F	± 4°F or ± 0.75%	30 sec
Fins	2 per 2 ft elevation of test section	0 to 900°F	± 4°F or ± 0.75%	30 sec
Inlet Air	2	0 to 300°F	± 4°F or ± 0.75%	30 sec @ 2 FPS
Outlet Air	2	0 to 500°F	± 4°F or ± 0.75%	30 sec @ 2 FPS
VELOCITY SENSOR				
Outlet Air (for flow rate measurement)	1	2-30 FPS	± 5% FR	30 sec
PRESSURE SENSORS				
Inlet Static (absolute)	1	Barometric (600-825 mm Hg)	1 mm Hg	1 sec
Test Section Differentials	3	0-1 mm Hg	± 0.3% FR	1 sec
HEATER AC SUPPLY MEASUREMENTS				
Voltage	3	0-500 V	± 0.5% FR	30 sec
Power	1	0-500 kW	± 2% FR	30 sec
HUMIDITY MEASUREMENT	1	0-98% RH 0-212 °F	± 3% RH ± 4°F or ± 0.75%	30 sec @ 2 FPS
RADIATION SENSOR (for heat flux measurement)	4	0-1.0 BTU/ft^2-sec	± 3% FR	1 sec
MOVABLE SENSORS[4]	1 each			
Pitot Tube Differential Pressure and Temperature with radiation shield	duct wall access ports located at 4 per 4 ft elevation of test section	2-30 FPS 0-1 mm Hg 0-500 °F	± 0.3% FR ± 4°F or ± 0.75%	30 sec @ 2 FPS
Hot Wire Anemometer	duct wall access ports located at 4 per 4 ft elevation of test section	0-30 FPS	± 1% FR	1 sec
Radiation Sensor (for emissivity measurement)	side wall access ports located at 1 per 4 ft elevation of test section	0-1.0 BTU/ft^2-sec	± 3% FR	1 sec

NOTES:

1. Additional quantities of each item may be incorporated with the maximum sampling limited by the data recording system. The data recording system must be capable of accepting up to 297 signals and must be capable of sampling the complete set of signals at a periodic rate not to exceed one minute.
2. The accuracy includes linearity and repeatability. If two values are presented, the greater value indicates the accuracy.
3. The response is the time required to equal 63% of instantaneous change.
4. A separate data recording system (in addition to that identified in Note 1) must be capable of recording the signals from the movable sensors.

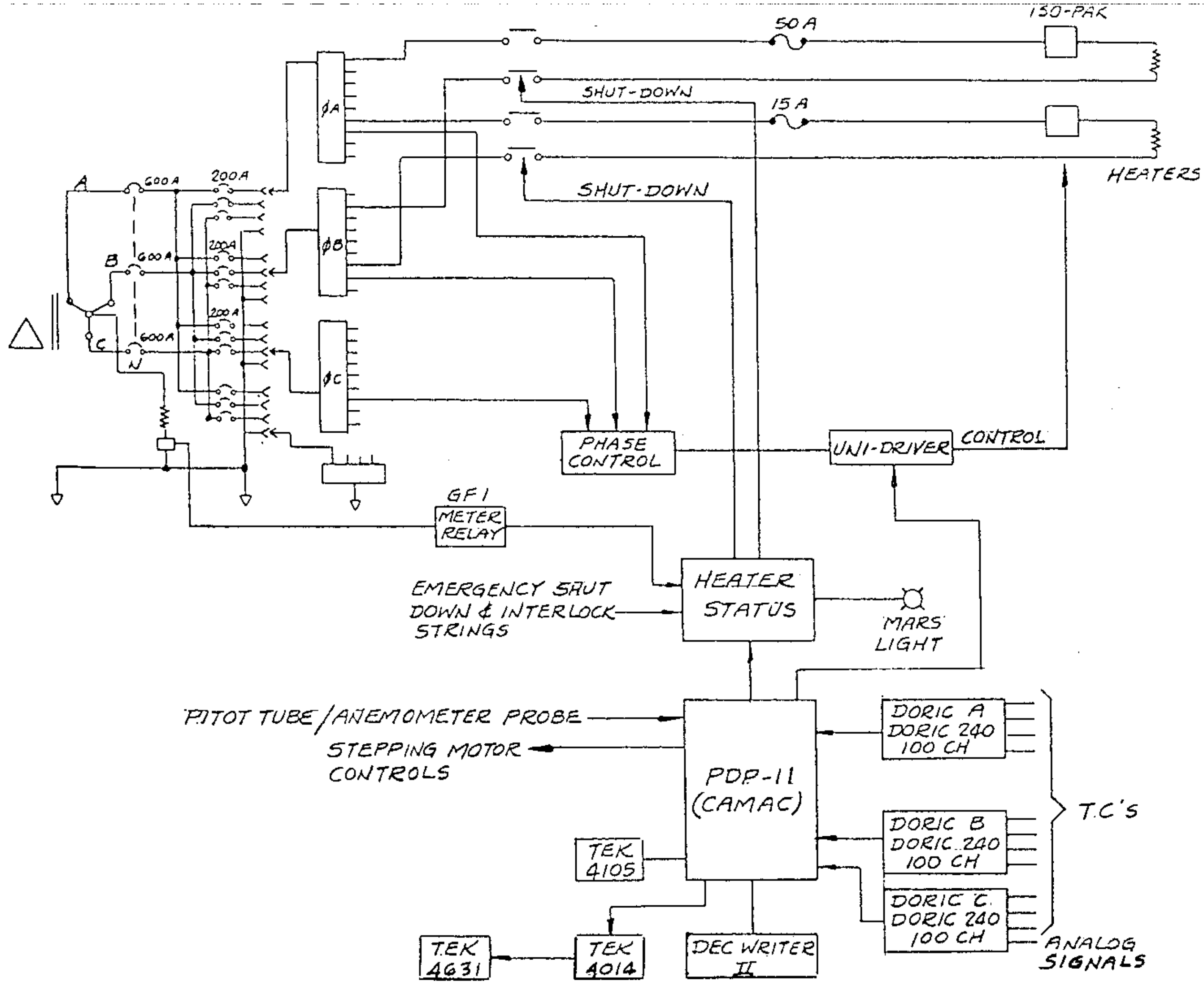


Figure 12. Electrical Control System Block Diagram RVACS/RACS

- Control temperature for each heater.

- A moderate number of calculated parameters (TBD).

The heater control algorithm treats each heater string as a separate entity. The heaters are numbered from 1 to 20. Heater 1 is the edge heater for the lowest two foot section, heater 2 the main heater for the first two foot section, etc. Each heater has the following associated variables:

IGNORE - Should heater be completely ignored (for checkout)?

TURNON - Is heater on? (can operate singly)

TRPTMP - Trip temperature. Maximum of any two TCs.

CTLTMP - Control temperature. Avg. of any four TCs.

CTLTYP - Control type (can be set singly for each heater).

CSTTMP - Constant temperature.

MATCH - Match control temperature of another heater.

CSTPWR - Constant power.

CSTUNI - Constant unidriver setting (for startup).

Various variables needed to implement the trip and control algorithms and to detect bad TCs.

1.4.2 DAS Software - Completed Activities

The data processing and display programs (from previous experiments) have been modified to allow for the larger number of parameters required by RVACS.

Camac Checkout Program

CAU - CAMAC Utility. General purpose, but tedious, CAMAC checkout.

TAI - Test Analog Input.

TDI - Test Digital Input.

TDO - Test Digital Output. Includes special command for Unidriver.

MKS - Test MKS Pressure Transducers.

SMC - Test Stepping Motor Controller.

Note: These programs have been used to check all CAMAC interfacing.

Data Acquisition

DAQTSK - Actual data acquisition task. This program, except for conversion algorithms, is written - has been partially tested.

DAQ - Operator interface for DAQTSK.

Heater Control

DAQTSK - Also performs heater control. Written but not tested.

HTR - Operator interface for heater control.

HCL - Heater control listing.

HCP - Heater control plotting.

1.4.3 DAS Software - Remaining Activities

- DAQTSK - Conversions for all non-TC parameters -- heater power, AC voltage, differential pressure, meteorological data.
- Probe (traverse mechanism) data acquisition and control.
- Special data reduction and displays.
- Lists/diagrams showing signal and power routing.

1.5 Test Plan

From the available design descriptions for the PRISM concept, it appears that the Air-Side Full-Scale Tests performed at ANL should encompass a range of heat fluxes, flow resistances and weather conditions that could exist following an inherent reactor shutdown wherein decay heat removal is entirely dependent upon the passive free convection effects of air flow between the reactor guard vessel (G.V.) and the surrounding duct wall. The initial (Phase I) test plan for the no-fin case is predicated on the following general conditions and strategy:

A. Thermal

1. Uniform G.V. wall temperature distribution to a maximum of 900°F (482°C).

2. Uniform G.V. heat flux to 2 kW/ft^2 (~ 20 kW/m^2).

3. Stepwise variable heat flux in the axial direction to simulate possible stratification of sodium temperatures in the reactor vessel.

4. Prototypic wall emissivities.

B. Fluid Dynamics

1. Very low flow resistance (initial test assembly loss coefficient, $K \cong 1.5$) to a loss coefficient of approximately ten ($K = 10$), referenced to the heated section cross-sectional area.

2. Flow channel dimensions will simulate a portion of the G.V. and duct wall design such that the air velocity profiles are prototypic.

C. It has been speculated that weather (particularly wind) conditions may affect the RVACS performance. Initially, the tests will be performed with the weather cap in place. Outside and inside ambient conditions will be monitored during testing and possible effects will be investigated. Selected test runs will be duplicated with the weather cap removed or replaced with low loss weather cap.

D. The test matrix as proposed at the ANL/GE meeting of 2/19/86 contains a large number of possible parametric sets for data collection. In addition, the possible number and location of air flow measurements (pressure and temperature) is large. This initial (Phase I) plan proposes to collect data at selected matrix points in relatively large parameter increments and a small number of pitot tube and thermocouple traverses to minimize experiment durations and data acquisition storage requirements. The results of Phase I operation will determine the required extent of the test matrix for Phase II.

E. The Phase I test matrix and possible Phase II (extended) test descriptions are presented in Table III.

TABLE III. RVACS Test Plan

Time Required (8 hrs/day) (Days)		Comments
	A Initial System Checkout	
5	1. Zero Flow, Zero Power - Simulate test run data acquisition and on-line processing for a "steady-state" condition.	Checkout for all instrumentation and DAS systems.
3	2. Zero Power, Forced Convection for range of Re = 1.5 and 2×10^5 (V = 15 and 30 ft/sec).	Characterize flow profiles.
	• Check for system leakage.	
	• Measure velocity profiles at six axial locations and 5-8 lateral positions.	
	• Record and process all system variables for "small" time increments correlated to traverse positions.	
11	3. Forced Convection at $V \cong 15$ ft/sec ($Re = 1.5 \times 10^5$), Power On.	Verify heater operations and control modes, bakeout heaters, charcterize forced convection operation as basis for subsequent data analysis.
	• Set fan to $V \cong 15$ ft/sec ($Re = 1.5 \times 10^5$)	
	• Heater Tests and Bakeout (constant temperature control mode).	
	• Zoned Power Tests.	
	• Stepwise heater operation for electrical integrity, one zone at a time, control mode -- constant temperature at 250°F, 600°F, 900°F. Heater temp. less than 1600°F.	Note the increase in radiative heat flux ($\sim T^4$) to collector wall as function of temperature

Table III. RVACS Test Plan (cont'd)

Time Required (8 hrs/day) (Days)		Comments
	• Record and process all system variables for "short" time increments - no traverses.	T(F) / $T^4(R^4)$ 250 / 2.5×10^{11} 600 / 1.3×10^{12} 900 / 3.4×10^{12}
	• All-Zone Power Tests	
	• Stepwise heater operation, all zones on, "equilibrium" tests for constant temperature control mode at 250°F, 600°F, 900°F periodically.	
	• Record and process selected variables for approach to steady state (will be relatively long-term since this is the bakeout phase).	
	• Record and process all system variables at three equilibrium stages, limited number of pitot tube traverses.	Heat flux and heat loss validation.
	• Heater Tests (constant heat flux control mode).	This activity is subject to the time limitations for part A (11 days) i.e., these tests may be deferred to Phase II).
	• Repeat all-zone power tests at 0.5, 1.0, and 1.5 kW/ft^2 (5, 10, and 15 kW/m^2).	
	• Repeat all-zone power tests for stepwise power increments by "zones" (no. is TBD).	

TABLE III. RVACS Test Plan (cont'd)

Time Required (8 hrs/day) (Days)		Comments
15	B. Free Convection Tests	
	1. Minimum entrance loss, weather cap <u>on</u> at stack exit (minimum exit loss).	Acquisition of basic data for performance evaluation of the RVACS no-fin design.
	• All-zone constant temperature control mode at 250°F 600°F, 900°F.	For free convection pretest calculations indicate that T_{GV} (°F) — Re — Avg. Qw (kW/m^2) 250 — 0.75×10^5 — 1.1 600 — 1.2×10^5 — 5.5 900 — 1.5×10^5 — 11.0
	• Zoned constant temperature control mode (stratification simulation) at 400°F, 600°F, 800°F, 1000°F.*	
	• All-zone constant heat flux control mode at 0.5, 1.0, and 1.5 kW/ft^2 (5, 10, and 15 kW/m^2).	*This activity is subject to the time limitation of part B (i.e. these may be deferred to Phase II).
	2. Combinations of higher entrance/exit loss conditions.	
	• Increased losses up to (possibly) K = 10 referenced to test section flow area. Pre-test predictions will be used to determine the additional entrance/exit loss to be added to achieve the desired Reynolds number range for 0.5×10^5 to 1.5×10^5. The actual number and configurations will be determined experimentally subject to the exit air temperature limitation of 300°F.	
	• For each loss configuration, repeat all or part of tests in B.1 above.	

TABLE III. RVACS Test Plan (cont'd)

Time Required (8 hrs/day) (Days)		Comments
	3. Minimum entrance and exit loss, weather cap <u>off</u>.	
	C. Possible Additional Tests - Phase II	
	1. During all of the tests above, the outside weather conditions will be monitored (particularly wind velocity and direction). If it appears that experiment data anomalies are related to changing meteorological conditions, procedures will be devised to account for these effects, perhaps by rerunning selected tests during selected meteorological conditions and/or utilizing alternate stack exit design.	
	2. It is possible that more detailed experiment data will be required for precision in computing performance data, e.g., intermediate values of temperature, heat flux and pressure loss settings.	
	3. Repeatability Tests, additional combined forced convection, free convection effects.	
	4. "Long Term" operation, ~ 5 days, perhaps during highly variable meteorological conditions.	

2.0 PRE-TEST ANALYSIS

2.1 Lumped Parameter Analysis

A variety of pre-test analyses of the RVACS test assembly have been performed to support the design and predict system performance for various operating conditions. The thermal model used is the same as that presented in Ref. [1]. However, the air flow model has been changed to use form losses instead of the previous factor "Ω": (Ω = pressure loss in heated zone/total system pressure loss). The model has also been upgraded to remove the previous assumption of air density being a linear function of temperature.

2.1.1 Model Development

The revised air flow equations are:

I. Net thermal head

$$\Delta P_h = \rho_o \, g \left[(1 - \bar{\rho}/\rho_o) L_h + (1 - \rho_s/\rho_o) L_s \right] \qquad (1)$$

where

ΔP_h = thermal head

ρ_o = air density at inlet

$\bar{\rho}$ = average air density in the heated zone

ρ_s = air density above heated zone

L_h = heated length

L_s = stack length

g = acceleration due to gravity

To calculate the average air density, $\bar{\rho}$, two assumptions are employed:

1. the air temperature rises linearly in the heated zone,* (constant heat flux case)

2. the pressure change is small relative to atmospheric pressure

from assumption no. 1, we have:

$$T_L = T_o + \frac{T_a - T_o}{L_h} L$$

where:

L = distance from inlet
T_L = air temperature at location L
T_a = air temperature at exit of heated zone

from assumption no. 2, we have, using the ideal gas law:

$$PV = RT_L$$

or: $\rho\ T_L = P/R = \text{constant}$

so that: $\rho = \dfrac{\rho_o\ T_o}{T_L} = \dfrac{\rho_o\ T_o}{T_o + (T_a - T_o)\ (\frac{L}{L_h})}$

then:

$$\bar{\rho} = \frac{1}{L_h} \int_o^{L_h} \rho\ dL$$

$$\bar{\rho} = \rho_o \left[\frac{\ln\ (T_a/T_o)}{T_a/T_o - 1}\right] \quad . \tag{2}$$

---

* Note:

An analysis was made to determine the error incurred when this assumption is retained for the case of the guard vessel wall temperature held constant. This demonstrated that an error in velocity of only 1.3% or less results for velocities of 5 fps or greater.

II. Pressure Losses

A. Friction Loss in Heated Zone

Again invoking the two assumptions given above, the frictional pressure loss, ΔP_{fh}, in the heated zone can be evaluated from:

$$\int_o^{L_h} dP_{fh} = \frac{2\ f_h\ G_h^2}{D_h\ \rho_o\ T_o} \int_o^{L_h} [T_o + (\frac{T_a - T_o}{L_h})\ L]\ dL$$

or

$$\Delta P_{fh} = \frac{f_h\ G_h^2}{D_h\ \rho_o} [L_h\ (1 + \frac{T_a}{T_o})] \tag{3}$$

where:

D_h = hydraulic diameter of the heated zone = $\frac{4 \text{ x flow area}}{\text{wetted perimeter}}$

G_h = air mass flow (flux) in heated zone

f_h = friction factor = $0.0791\ Re_h^{-0.25}$

Re_h = Reynold's No. = $\frac{G_h\ D_h}{\mu}$

μ = air dynamic viscosity

Subscript h denotes heated zone

B. Friction Loss in Unheated Zone (Stack)

The air temperature is constant in this region so the pressure loss is:

$$\Delta\ P_{fs} = \frac{2\ f_s\ G_h^2\ L_s}{D_s\ \rho_s} (\frac{A_{fh}}{A_{fs}})^2 \tag{4}$$

where:

D_s = hydraulic diameter of stack

ρ_s = air density in stack

A_{fh} = flow area in heated zone

A_{fs} = flow area in stack

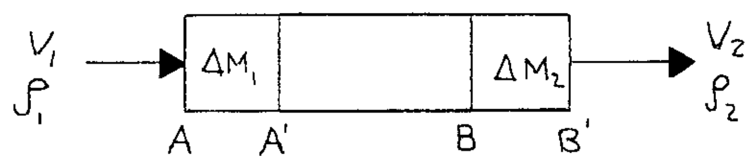
f_s = friction factor in stack = $0.0791\ Re_s^{-0.25}$

Re_s = Reynold's No. in the stack

Subscript s denotes region above heated zone

C. Acceleration Pressure Loss

To determine the acceleration pressure loss, ΔPa, it is convenient to use a control volume that moves with the flow (Eulerian coordinates) thereby ensuring that the same body of fluid particles are preserved in momentum calculations. Consider the following sketch:



At time t the vertical surfaces of the control volume lie at locations A and B. In an added incremental time Δt the surfaces move to A' and B' respectively. For steady flow, the small masses of fluid between A and A', and B and B' are respectively:

$\Delta m_1 = \rho_1\ V_1\ A_F\ \Delta t$; where A_F = area of the control volume normal to the flow

$\Delta m_2 = \rho_2\ V_2\ A_F\ \Delta t$

but since, $\rho_1\ V_1 = \rho_2\ V_2$; $\Delta m_1 = \Delta_{m2} = \Delta m$ and; $\Delta m = \dot{m}\Delta t$, where $\dot{m}$ is the mass flow rate. Thus, in time Δt there is a momentum loss from the control volume of magnitude $\dot{m}\Delta tV_1$ at the inlet and a gain of, $\dot{m}\Delta tV_2$ at the exit. The net change; $\dot{m}\Delta t\ (V_2 - V_1) = F\ \Delta t$, where $F\Delta t$ is the net impulse applied to the mass of fluid. We then have:

$$\frac{F}{A_F} = \Delta P_a = G\ (V_2 - V_1) = G\ (\frac{G}{\rho_2} - \frac{G}{\rho_1})$$

or:

$$\Delta P_a = G^2 \left(\frac{1}{\rho_2} - \frac{1}{\rho_1}\right)$$

Thus for the heated zone:

$$\Delta P_a = G_h^{\ 2} \left(\frac{1}{\rho_s} - \frac{1}{\rho_o}\right) \tag{5}$$

D. Form Losses

System pressure losses due to expansions, contractions, bends, etc. may be expressed as:

$$\Delta P_K = K_{loss,i} \frac{\rho_i u_i^{\ 2}}{2}$$

where the subscript i denotes local geometric conditions in the system and $K_{loss,i}$ is a constant whose value is appropriate for the geometric change. Referred to the heated zone flow the above equation becomes:

$$\Delta P_K = K_{loss,i} \frac{\rho_i u_h^{\ 2}}{2} \left(\frac{A_{fh}}{A_{fi}}\right)^2 = K_{loss,i} \frac{\rho_i G^2}{2 \rho_o^{\ 2}} \left(\frac{A_{fh}}{A_{fi}}\right)^2$$

Re-defining the form loss constant as:

$$K_{loss} = K_{loss,i} \left(\frac{A_{fh}}{A_{fi}}\right)^2 \tag{6}$$

Then:

$$\Delta P_{K_{loss}} = K_{loss} \frac{\rho_i G^2}{2 \rho_o^{\ 2}} \tag{7}$$

Summing the system pressure losses we have:

$$\Sigma \text{ losses} = \frac{G^2}{2\rho_o} \left\{ \frac{\rho_i}{\rho_o} K_{loss} + \frac{2 f_h L_h}{D_h} \left[\frac{T_a}{T_o} + 1 \right] \right.$$

$$\left. + \frac{4 \rho_o f_s L_s}{\rho_s D_s} \left(\frac{A_{fh}}{A_{fs}} \right)^2 + 2 \left[\frac{T_a}{T_o} - 1 \right] \right\} \qquad (8)$$

For steady flow the sum of system pressure losses must equal the net thermal driving head whereby we equate Eq. (1) to Eq. (8). The resulting equation is solved by iteration to find converged values of G, Reynolds Nos., friction factors, convective heat transfer coefficient, average air density, and exit air temperature. The thermal analysis then proceeds as before to determine temperature of the guard vessel and duct wall simulators.

2.1.2 Calculated RVACS Test Assembly Performance

The foregoing equations were incorporated in the previous model of Ref. [1] and the resulting FORTRAN program is listed in Appendix I. The code was then used to calculate system performance based upon current design parameters for the simulation of PRISM. Table IV presents the important dimensions and other parameters used in the calculations. As indicated, the overall system loss coefficient was treated as a parameter. Table V delineates the estimated system losses in a "wide open" configuration and Table VI shows the basis for using a loss coefficient of 1.0 for an ELGO weather cap which has been selected to cover the stack.

Figure 13 depicts a system performance map in terms of Reynold's numbers and air temperatures vs. heater input power (flux) for the range of loss coefficients assumed. These results show the deleterious effects of high form losses; however, even for the high loss cases, Reynold's numbers indicating turbulent flow are predicted and air exit temperature levels do not exceed the system limit of 300°F, even at maximum heater power (2 kW/ft^2). With an estimated overall loss coefficient of ~ 1.5 for the test assembly in the "wide open" configuration, Reynold's numbers > 1.0×10^5 should be easily achievable even at relatively low heater power levels. The map also indicates turbulent flow even for high losses and low heater power.

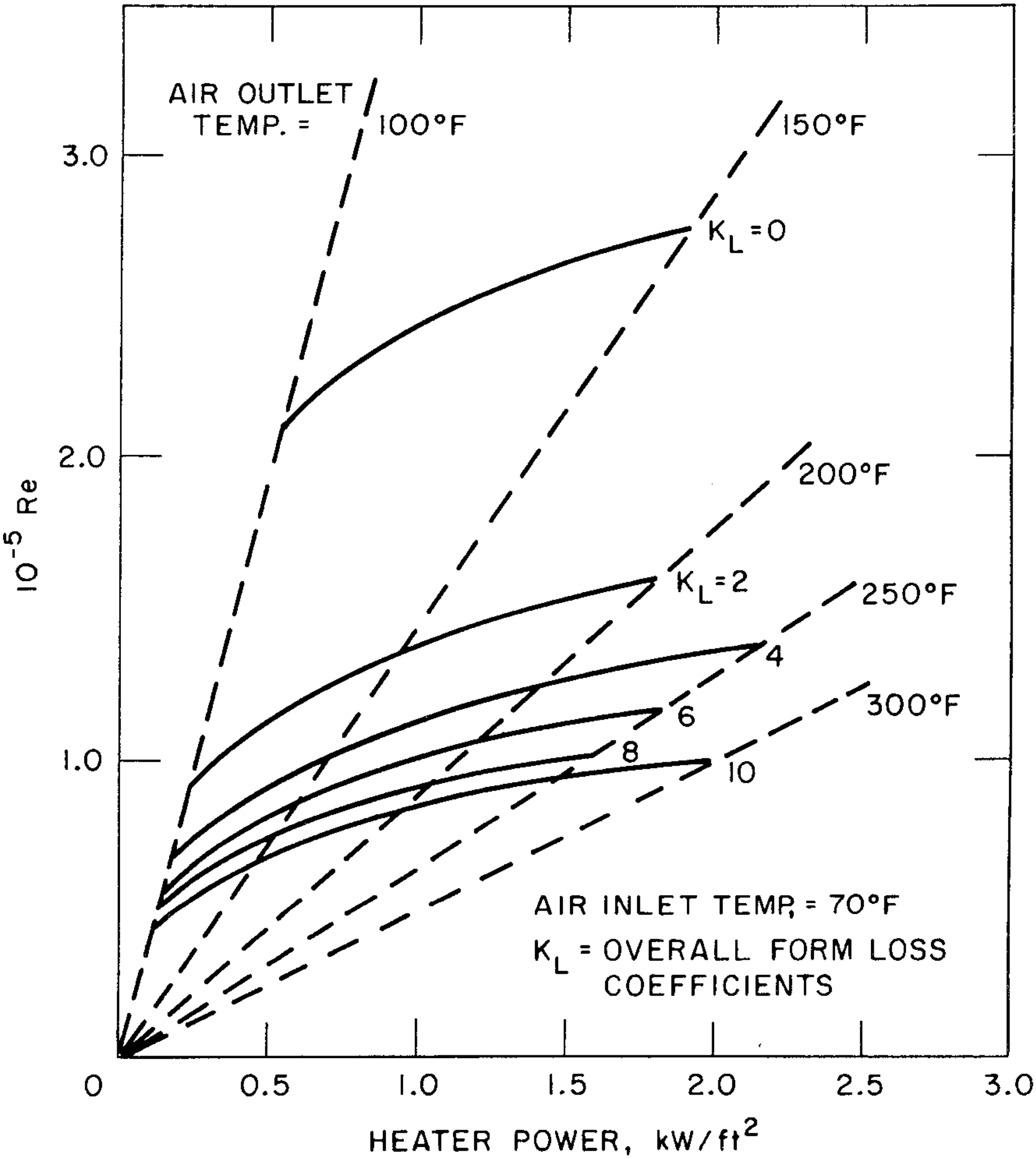


Figure 13. Test Assembly Performance Map

Table IV. RVACS Test Assembly Parameters

Heated length = 22 ft.
Stack height = 50 ft.
Heated channel cross section = 12" x 52".
Stack channel cross section = 18" x 52".
Emissivity of surfaces = 0.7.
Inlet air temperature = 70°F.
Inlet air density = 0.0748 lb/ft^3.
Overall K_{Loss} (Referred to inlet) = 0 to 10.

Table V. RVACS Loss Coefficients for GE Simulation

		Local	Inlet
1.	Entrance (Re-entrant)	0.85	0.85
2.	Heated zone to stack transition	0.11	0.11
3.*	S-flue H/W ≅ 3.0 R/W = 2.0 2-60° bends (0.67 of 90° ea.)	0.15	0.067
4.	Weather Cap		
	ELGO or none	1.0	0.44
Overall:	ELGO cap or none	2.11	1.467

*2-60° Bends: each has a loss that is ~ 67% of a 90° bend.

Table VI. Estimated Loss Coefficient for ELGO Weather Cap

$$\Delta p = K\rho_{air}\frac{u^2}{2} = \rho_{H_2O} \cdot g \cdot h$$

$$K = \frac{2\ \rho_{H_2O}}{\rho_{air}} \cdot \frac{g \cdot h}{u^2}$$

$\rho_{H_2O} = 997\ kg/m^3$

$\rho_{air} = 1.0\ kg/m^3$

$g = 9.8\ m/s^2$

h = pressure loss - in/H_2O

u = air exhaust velocity - ft/min

$$K = \frac{2 \times 997 \times 9.8 \times (1/12) \times 0.3048}{1.0 \times \left(\frac{.3048}{60}\right)^2} \cdot \frac{h}{u^2}$$

$$K = 1.923 \times 10^7 \frac{h}{u^2}$$

u*	u^2	h*	$1.923 \times 10^7\ h/u^2 = K$
300	9×10^4	0.002	0.427
400	1.6×10^5	0.004	0.481
500	2.5×10^5	0.007	0.538
600	3.6×10^5	0.011	0.588
700	4.9×10^5	0.017	0.667
800	6.4×10^5	0.025	0.751
900	8.1×10^5	0.035	0.831
1000	1×10^6	0.045	0.865
1100	1.21×10^6	0.057	0.906
1200	1.44×10^6	0.069	0.921

*Values of u and h are taken from ELGO data.

This is further illustrated in Fig. 14 which again indicates satisfactory system performance for a wide range of loss coefficients. These results were developed for the condition of the guard vessel temperature held constant at 900°F.

Additional parametric calculations were made to determine other system responses, particularly wall temperatures, to variations in loss coefficients, emissivities and heater power levels. Results of these calculations are shown in Table VII. Once again the predicted air exit temperatures are all well within the 300°F limit. However, a few cases that assume high losses and/or high heater power levels, lead to high guard vessel and duct wall temperatures; e.g. guard vessel temperatures well above 1000°F. This will also be an initial system operating limit; therefore such cases, which may challenge system integrity will be avoided, at least in early tests.

An additional set of calculations were made to investigate the size of the guard vessel to duct wall gap on system performance. Previous calculations led to a conclusion [Ref. 1] that the gap size only weakly affected the system. This conclusion is now considered erroneous because it was based on the assumption of low exit/entrance pressure losses, i.e., a value of Ω in the range of 0.5 was used which is equivalent to assuming that the pressure loss in the heated zone represents about half the total system pressure drop. This is equivalent to overall entrance/exit loss coefficients of small fractional values (see Appendix I of Ref. [1]).

Now realizing that system pressure losses are dominated by form losses, the effect of gap size on system performance was re-calculated leading to a much different conclusion regarding its effect. This is demonstrated in Figures 15 to 17. Figure 15 shows the temperature lowering potential afforded by reduction in gap size when any appreciable entrance/exit pressure losses exist in the system. The lower curve is unachievable but shown to indicate the basis of the previous conclusion of low system sensitivity to gap size when losses are small. The other, more reasonable curves, show temperature reductions on the order of 300°F may be achieved by gap size reduction from the current value of 12 inches to ~ 5 to 6 inches. Although the curves show minima in the 3 to 4 inch range, such small gaps may be infeasible for reactor construction.

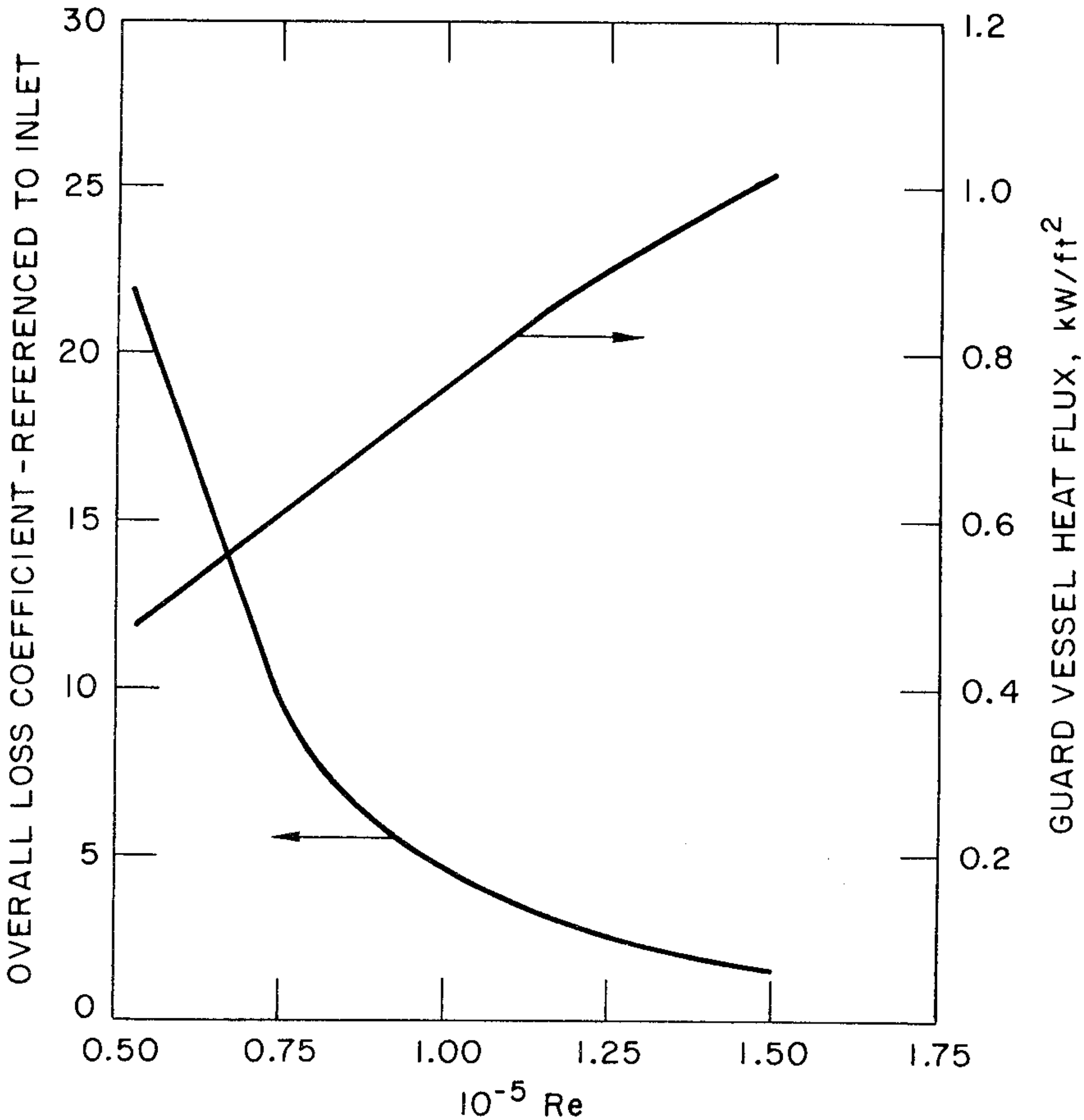


Figure 14. Performance for Guard Vessel Temperature = 900°F

Table VII. Pretest Parametrics for the RVACS PRISM Experiments

Case No.	K	ϵ	Q_w (kW/ft^2)	$\bar{U}$ (ft/s)	10^{-5} Re	Ta (°F)	T_{GVO} (°F)	T_{GV} (°F)	T_{DO} (°F)	T_D (°F)	h ($B/hr\text{-}ft^2$)	$10^3 \Delta P_T$ (psi)
1	1.5	0.7	1.0	16.2	1.49	148	850	927	648	725	2.51	4.07
2	1.0	"	"	17.7	1.64	140	809	879	587	657	2.72	3.73
3	4.0	"	"	12.5	1.14	172	988	1089	842	944	2.02	5.16
3a	10.0	"	"	9.63	0.849	206	1184	1319	1088	1224	1.60	6.56
4	0.2	"	"	22.7	2.14	124	716	770	441	495	3.36	2.94
5	0.1	"	"	24.0	2.27	121	699	749	414	465	3.51	2.80
6	0.4	"	"	20.9	1.96	129	745	804	487	546	3.13	3.19
7	1.5	0.5	"	16.2	1.49	148	897	975	600	678	2.51	4.07
8	"	0.6	"	"	"	"	871	948	627	704	"	"
9	"	0.8	"	"	"	"	833	910	665	742	"	"
10	"	1.0	"	"	"	"	807	885	690	768	"	"
11	"	0.7	0.1	7.57	0.738	85.9	238	253	141	157	1.43	0.67
12	"	"	0.25	10.3	0.990	99.4	386	415	226	255	1.81	1.66
13	"	"	0.5	12.9	1.22	117	567	615	368	415	2.15	2.60
14	"	"	0.75	14.7	1.38	133	716	779	509	572	2.36	3.38
15	"	"	1.5	18.3	1.66	174	1094	1199	916	1020	2.74	5.27
16	"	"	2.0	20.1	1.78	200	1327	1457	1172	1302	2.89	6.32
17	0.2	"	1.5	25.4	2.35	144	911	985	643	716	3.62	3.89
18	"	"	2.0	27.3	2.49	163	1094	1186	847	940	3.79	4.76

Note: These calculations were made for an inlet air temperature of 70°F. Other temperatures listed are for bottom and top of heated zone.

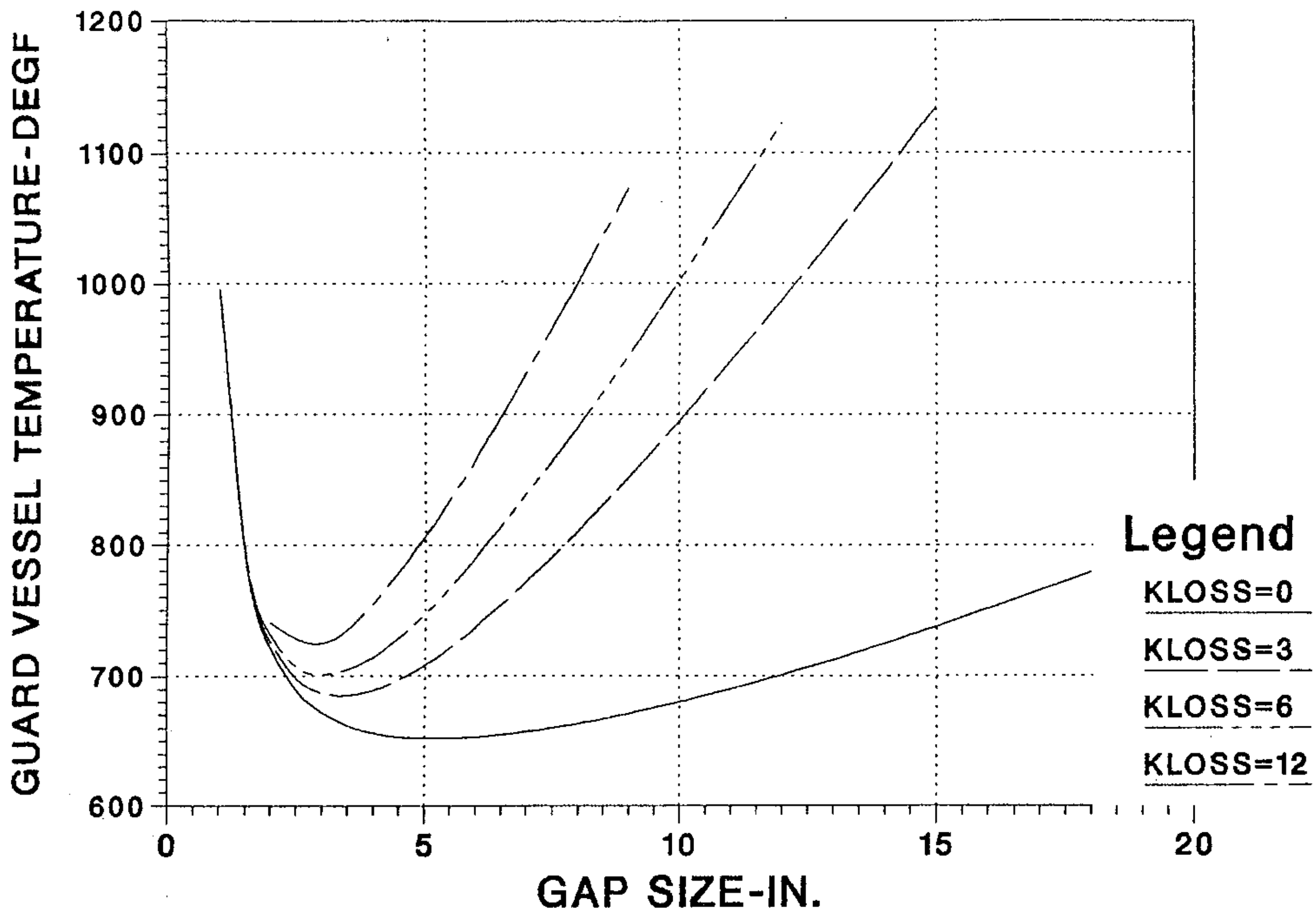


Figure 15. Effect of Guard Vessel to Collector Gap Size on Guard Vessel Temperatures, Q = 1 kW/ft**2

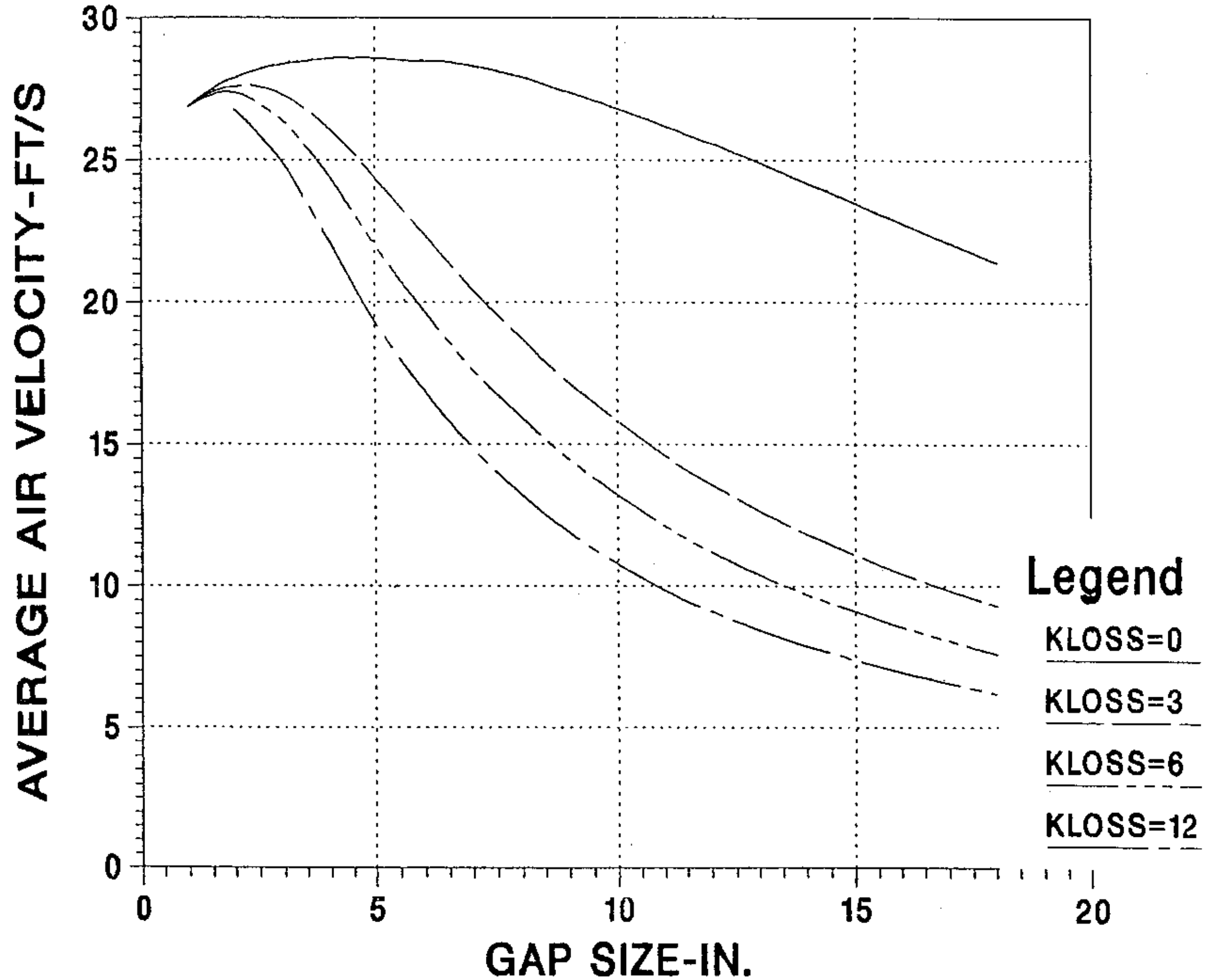


Figure 16. Effect of Guard Vessel to Collector Gap Size on Air Velocity, Q = 1 kW/ft**2

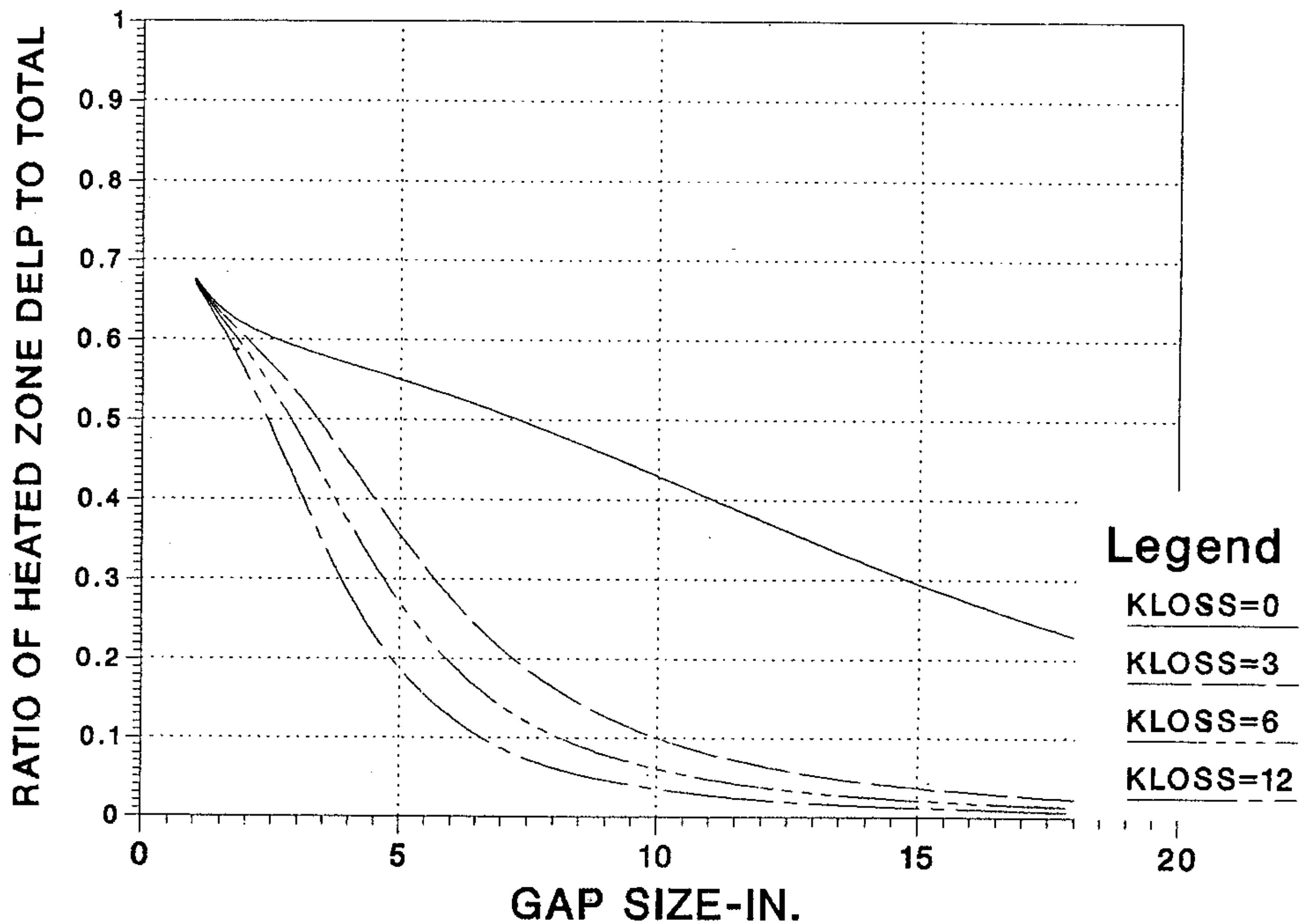


Figure 17. Effect of Guard Vessel to Collector Gap Size on Relative System Pressure Drops, QW = 1 kW/ft**2

The temperature drop with initial gap size reduction occurs because until the friction loss in the heated zone becomes significant, the mass flow rate tends to remain essentially constant. This causes the velocity to increase thereby increasing the heat transfer coefficient and concommitant heat removal at lower ΔT's.

The velocity response to gap reduction is depicted in Fig. 16; it turns over at the points of temperature minima.

Finally Fig. 17 shows relative pressure drop in the heated zone. This clearly shows the dominance of the entrance/exit losses at the larger gap sizes.

Therefore, the previous conclusion on the insensitivity of the system to gap size is reversed. These current results indicate that a potential for considerable improvement in performance can be achieved with a reduced gap size.

2.2 COMMIX-1A Analysis

RVACS Turbulence Modeling Using COMMIX-1A

The design and licensing of a RVACS system will require a detailed understanding of the air-side performance of the natural convecting air stream including such uncertainties as variation in the circumferential variations in the gap between the guard vessel and collector, partially blocked entrances, etc. The purpose of this analysis is to make use of the data obtained in the RVACS experiment to validate COMMIX as a useful tool in the prediction of air-side-velocities and heat transfer coefficients.

COMMIX-1A provides two turbulence models, viz. a constant turbulence model and a one-equation (k) model. Both have been tried in simple representations of the heated zone of RVACS; results have been unsatisfactory for both methods.

Increasing the molecular viscosity of air to simulate the effect of turbulence and then providing such a value as input to COMMIX for the constant viscosity model simply does only that, i.e., it makes the fluid more viscous but does not treat the turbulent eddy diffisuivity. Thus, a turbulent flow pattern does not develop and the flow profile across the channel is characteristic of laminar flow. An example is shown in Fig. 18 where the channel exit flow is shown for isothermal conditions with the normal molecular viscosity of the air increased by a factor of 100. The parabolic shape indicates laminar flow.

Calculations were then made using the one-equation turbulence option (k model) available in COMMIX-1A. These results, using default values of adjustable parameters showed the calculated turbulent intensities to be too high. The wall stress was excessive as evidenced by the high pressure drop through the system. Changing parameters in the near-wall model reduced the pressure drop to a value reasonably close to that prediced by a lumped parameter model using a friction factor for fully developed turbulent flow. It was hoped that this change would favorably resolve other calculated quantities, e.g., turbulent kinetic energy magnitude and shape, velocity profiles and magnitude of turbulent viscosity. However, such was not the case and a literature search was then made to find target values of these quantities to be used in further calibration runs. The best data for RVACS calculations to be checked against was found in [2]. This study included both symmetric and asymmetric heating of two channel walls with the latter condition representative of RVACS operation.

Our initial calculations with the one equation model were for the simplest case, i.e., for isothermal conditions. Then target curves were those shown in Fig. 19 (velocity profiles) and Fig. 20 (turbulent kinetic energy) for Grasshof No. = 0.0. Leaving the near-wall adjustable constants as previously determined, a large number of parametric runs were made adjusting remaining constants. None of these calculations provided satisfactory results. The best solutions are depicted in Figs. 21 and 22. Comparing Fig. 22 to Fig. 20 shows the COMMIX calculation yielding turbulent kinetic energy levels approximately a factor of four greater than target values. Similarly comparison of Fig. 21 with Fig. 19 shows that COMMIX predicts a velocity profile that is much too flat.

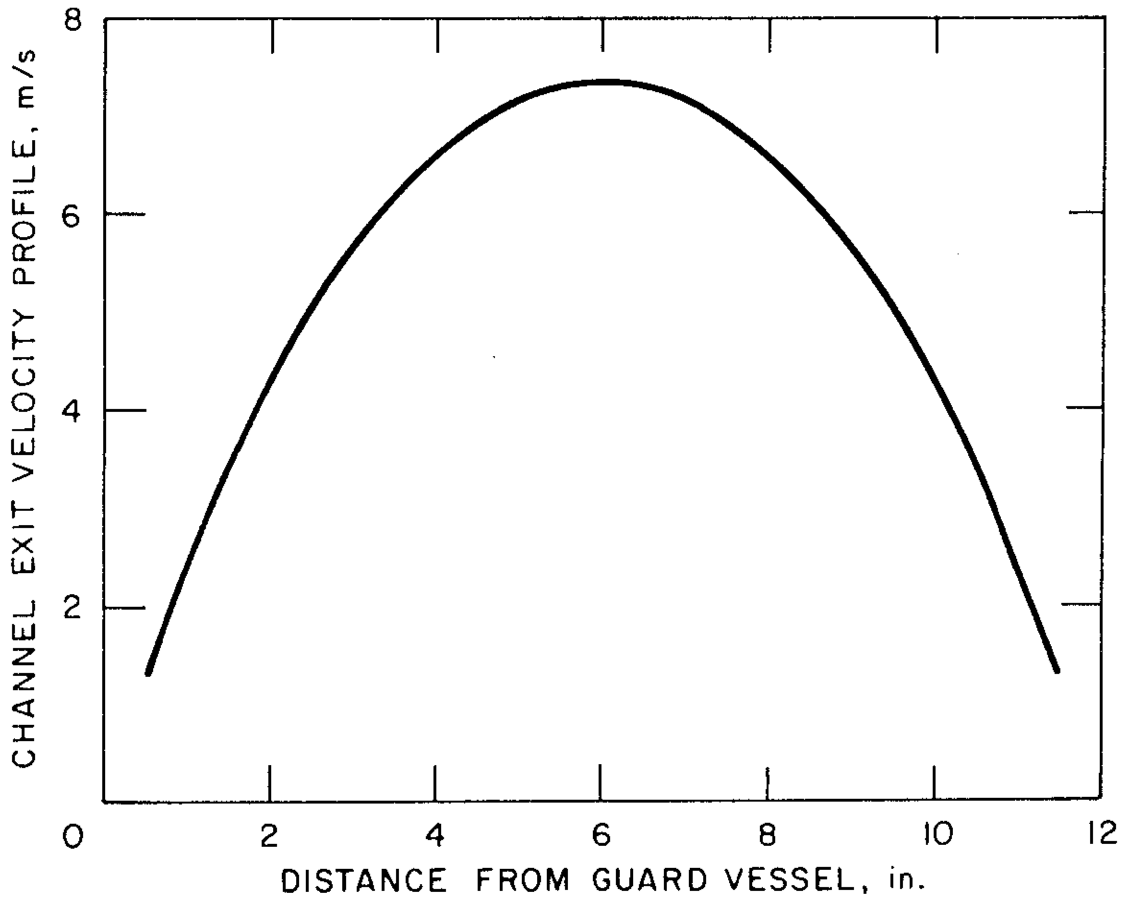


Figure 18. Air Velocity Channeling in RVACS U = 5 M/S,
Q = 0 KW/M**2, MUT/MU = 100

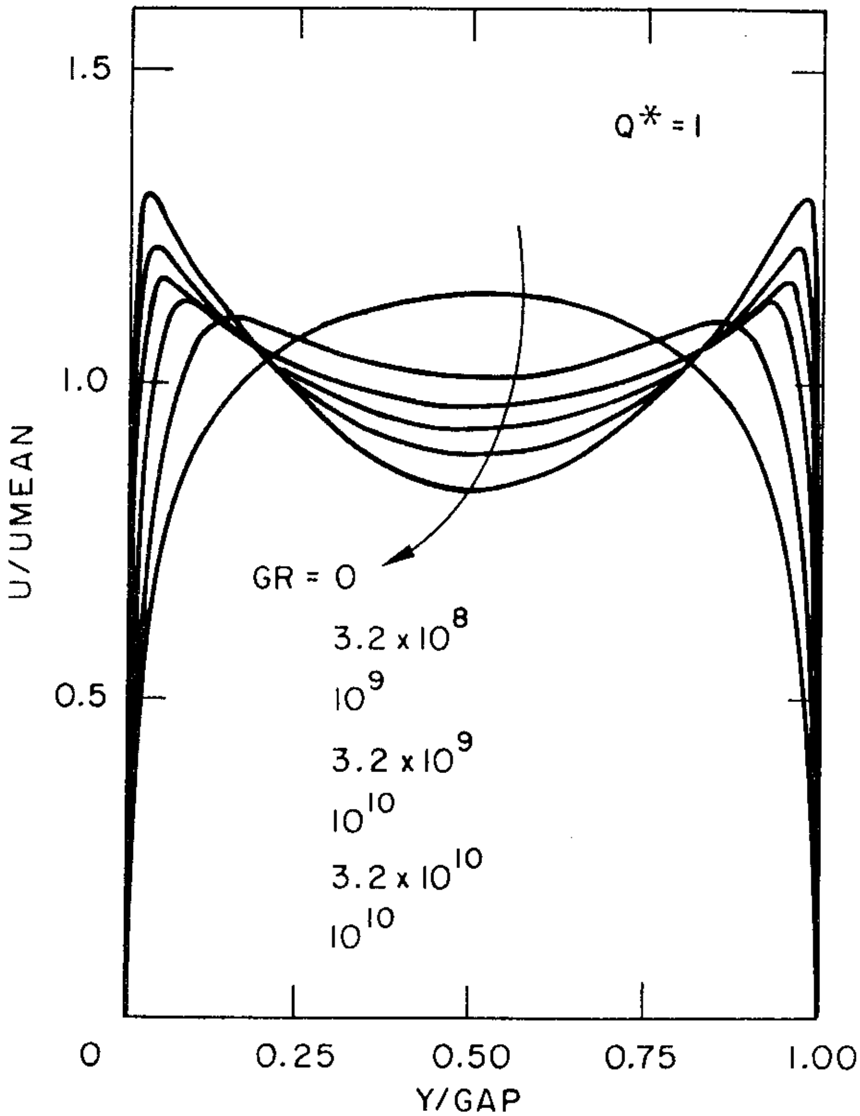


Figure 19. Velocity Profiles for Symmetric Heating

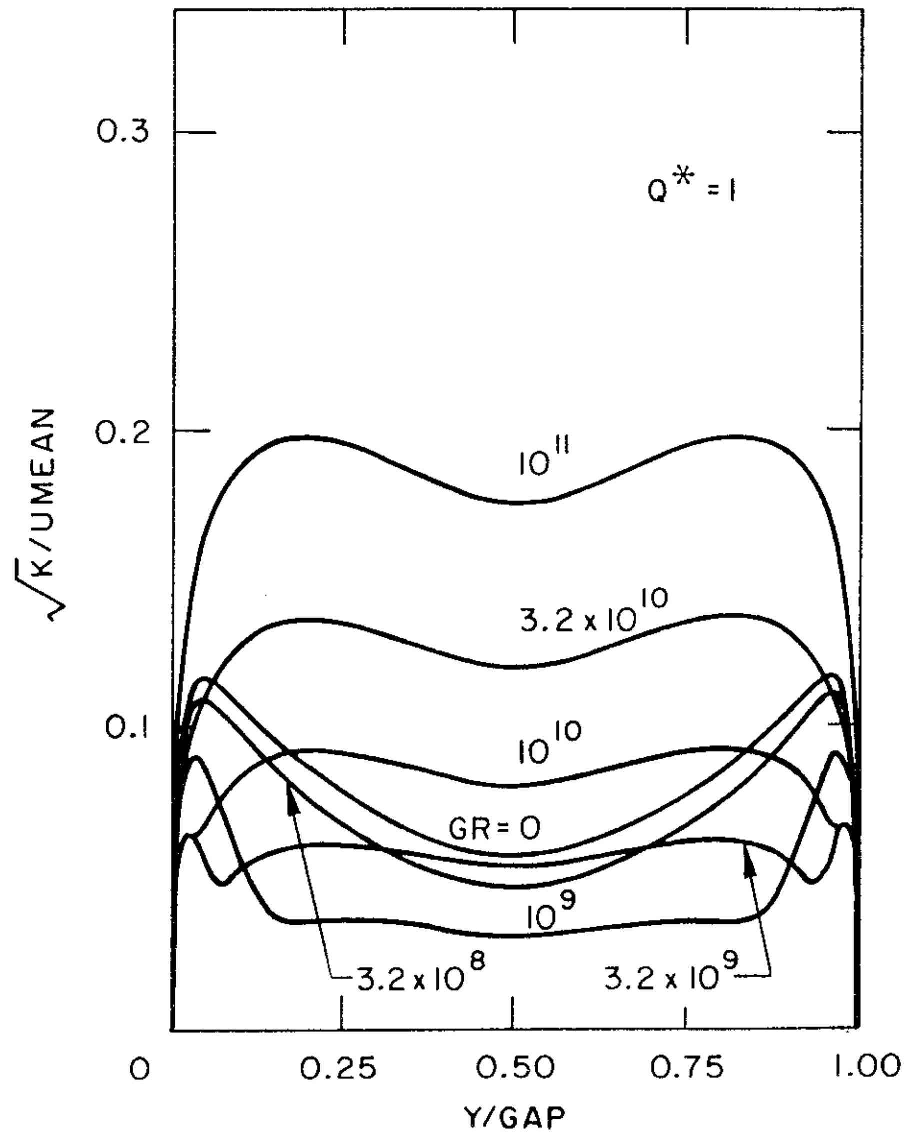


Figure 20. Turbulent Kinetic Energy for Symmetric Heating

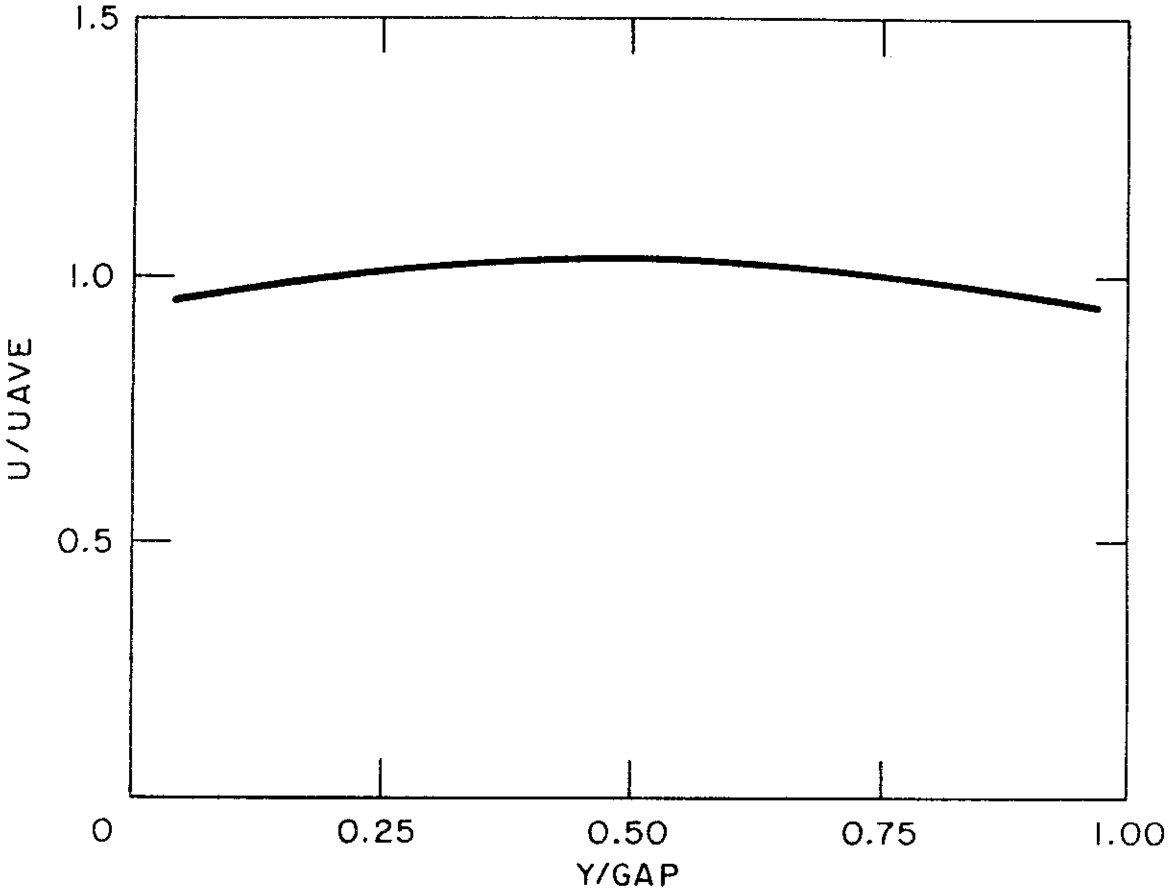


Figure 21. RVACS Velocity Profile at Exit U = 5 M/S, Q = 0.0, 1-EQ Turb. Model

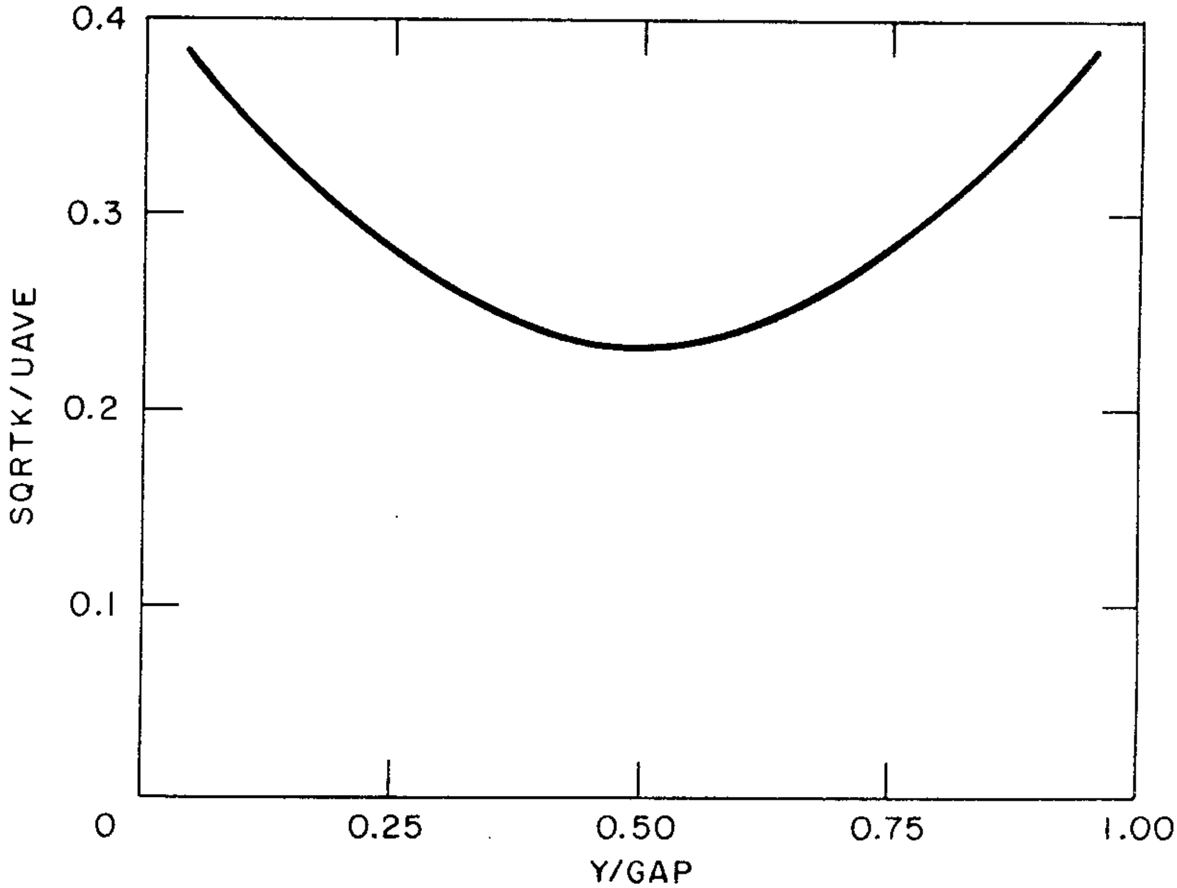


Figure 22. RVACS Turb. Kinetic Energy Profile at Exit
U = 5 M/S, Q = 0.0, 1 EQ Turb. Model

These failures to achieve acceptable results for turbulence modeling using COMMIX-1A and the one-equation model were discussed with code developers at ANL CT Division. It was concluded that the turbulence models in COMMIX-1A were probably inadequate for our purposes, having been developed with emphasis on treating flow through rod bundles. We were advised that superior models are available in COMMIX-1B which contains two-equation (k-ε) modeling of turbulence and that a much greater potential for acceptable results is expected with its use. Unfortunately, to date, COMMIX-1B does not treat air side radiation heat transfer. Nonetheless, current plans are to use COMMIX-1B for RVACS turbulence modeling and to simulate radiation heat transfer by other means.

3.0 REFERENCES

1. T. C. Chawla, et al., "Modeling of the Air-Side Performance of the RVACS Shutdown Heat Removal System--Status of Experimental Program," ANL-PRISM-8 (January 1986).

2. J. R. Pietrzyk and M. E. Crawford, "A Numerical Investigation of Turbulent Mixed Convection in Vertical Annular Channels," ASME, HTD-Vol. 42, Fundamentals of Forced and Mixed Convection, Eds. A. Kulacki and R. D. Boyd, 23rd National Heat Transfer Conference, Denver, Colorado (August 4-7, 1985).

APPENDIX I

This appendix presents a FORTRAN source code listing of the program used to obtain the results presented in Section 2 of this report.

FILE: SMOOTHBR FORTRAN A1 ANLVM VM/SP 405 CMS

```
C
C     $$$$$$$$$$$$$$$$$$$$$$$$$   THIS IS A SMOOTH CHANNEL MODEL-NO FINS
C
C     OR RIBS  $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
C
C     THIS PROGRAM IS FOR SHRS WITHOUT FINS OR RIBS I.E. FOR SMOOTH
C     CHANNELS.  THE BOUYANCY DRIVEN AIR FLOW IS BASED ON EQ'S. DERIVED
C     BY P.A. LOTTES. REMAINING FORMULATIONS BY F.B. CHEUNG.
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
C     UNITS OF OUTPUTS ARE BRITISH 4-15-86
C
C     $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C     *
C     ******************************************************************
C     *
C     *****************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL L,LH,MU,NU,K,LS,KLOSS,KLOSSI
      DATA RHO,GRAV,BETA,TO,CP,MU,ALPHA,NU,K,SIGMA,AE,AH
     1 /1.200,9.8,0.00367,294.4,1.E3,1.83E-5,
     2  2.25E-5,1.58E-5,0.0257,5.67E-8,1.0,1.0/
      DATA CCONV/0.01/
1     WRITE(6,3)
3     FORMAT(1X,'INPUT H, W, HS AND WS IN INCHES')
      READ(5,*) H,W,HS,WS
      WRITE(6,4)
4     FORMAT(1X,'ENTER STACK HEIGHT AND HEATED LENGTH IN FEET')
      READ(5,*) LS,LH
      LH=0.3048*LH
      LS=0.3048*LS
      L=LS+LH
      WRITE(6,5)
5     FORMAT(1X,'ENTER VALUE OF KLOSSI AND EMISSIVITIES FOR RVACS & RV')
      READ(5,*) KLOSSI,EPS,EPSRV
      H=H/39.37
      W=W/39.37
      HS=HS/39.37
      WS=WS/39.37
      AFH=H*W
      AFS=HS*WS
      DH=4.0*W*H/(2.0*(W+H))
      DHS=4.0*WS*HS/(2.0*(WS+HS))
      AFL=AFH
      KLOSS=KLOSSI*((AFH/AFL)**2)/(RHO**2)
      BRH=H*39.37/12.
      BRW=W*39.37/12.
      BRHS=HS*39.37/12.
      BRWS=WS*39.37/12.
      BRLS=LS/0.3048
      BRLH=LH/0.3048
      BRAFH=AFH/(0.3048**2)
      BRAFS=AFS/(0.3048**2)
      BRDH=DH/(0.3048)
```

FILE: SMOOTHBR FORTRAN A1 ANLVM VM/SP 405 CMS

```
      BRDHS=DHS/(0.3048)                                                SM000560
      WRITE(6,6) BRH,BRLH,BRLS,KLOSSI,EPS,EPSRV,BRW,BRDH,BRHS,BRWS,BRDHSSM000570
     >,BRAFH,BRAFS                                                      SM000580
      WRITE(50,6) BRH,BRLH,BRLS,KLOSSI,EPS,EPSRV,BRW,BRDH,BRHS,BRWS,    SM000590
     >BRDHS,BRAFH,BRAFS                                                 SM000600
6     FORMAT(1X,'H=',F10.4,2X,'LH=',F10.4,2X,'LS=',F10.4,2X,            SM000610
     1'KLOSS=',F10.4,2X,'EPS=',F10.4,2X,'EPSRV',F10.4,2X,'W=',F10.4,2X,'SM000620
     2 DH=',F10.4,/,1X,'HS=',F10.4,2X,'WS=',F10.4,2X,'DHS=',F10.4,      SM000630
     32X,'AFH=',F10.4,2X,'AFS=',F10.4,///)                              SM000640
7     WRITE(6,8)                                                        SM000650
8     FORMAT(1X,'ENTER VALUE OF HEAT FLUX IN KW/M**2')                  SM000660
      READ(5,*) QW                                                      SM000670
      QW=1.E3*QW                                                        SM000680
      EPSW=EPS                                                          SM000690
      EPSS=EPS                                                          SM000700
C     THE FOLLOWING ASSIGNMENT OF AW=400 IS AN INITIAL GUESS            SM000710
      AW=400.                                                           SM000720
C     THE FOLLOWING ASSIGNMENT OF G AND TA IS AN INITIAL GUESS          SM000730
      G=1.0                                                             SM000740
      TA=350.                                                           SM000750
      RHOBAR=(RHO*DLOG(TA/T0))/(TA/T0-1.0)                              SM000760
      RHOA=RHO*(T0/TA)                                                  SM000770
      RHOI=RHO                                                          SM000780
11     RE=G*DH/MU                                                       SM000790
      RES=(G*DHS/MU)*(AFH/AFS)                                          SM000800
C     BLASIUS FRICTION FACTOR                                           SM000810
      F=0.0791*(RE**(-0.25))                                            SM000820
      FS=0.0791*(RES**(-0.25))                                          SM000830
      DPFH=F*LH*(1.0+TA/T0)/(DH*RHO)                                    SM000840
      DPFS=2.0*FS*LS*((AFH/AFS)**2)/(RHOA*DHS)                          SM000850
      DPAC=(TA/T0-1.0)/RHO                                              SM000860
      DPFORM=KLOSS*RHOI/2.0                                             SM000870
      HD=RHO*GRAV*((1.0-RHOBAR/RHO)*LH+(1.0-RHOA/RHO)*LS)               SM000880
C     WRITE(6,*) RHO,GRAV,RHOBAR,LH,RHOA,LS,HD,TA                       SM000890
C     WRITE(50,*) RHO,GRAV,RHOBAR,LH,RHOA,LS,HD,TA                      SM000900
      SUMLOS=DPFH+DPFS+DPAC+DPFORM                                      SM000910
      GNEW=(HD/SUMLOS)**0.5                                             SM000920
      TA=T0+QW*LH/(GNEW*CP*H)                                           SM000930
      RHOBAR=(RHO*DLOG(TA/T0))/(TA/T0-1.0)                              SM000940
      RHOA=RHO*(T0/TA)                                                  SM000950
C     WRITE(6,*) GNEW,TA,RHOBAR,RHOA                                    SM000960
      DELG=GNEW-G                                                       SM000970
      IF(DABS(DELG).LT.0.01) GO TO 12                                   SM000980
      G=G+DELG*CCONV                                                    SM000990
C     WRITE(6,*) DELG,GNEW,G,CCONV                                      SM001000
C     WRITE(50,*) DELG,GNEW,G,CCONV                                     SM001010
      GO TO 11                                                          SM001020
12    G=GNEW                                                            SM001030
      TA=T0+QW*LH/(G*CP*H)                                              SM001040
      RHOA=RHO*(T0/TA)                                                  SM001050
      RHOBAR=(RHO*DLOG(TA/T0))/(TA/T0-1.0)                              SM001060
      RE=G*DH/MU                                                        SM001070
      RES=(G*DHS/MU)*(AFH/AFS)                                          SM001080
C     BLASIUS FRICTION FACTOR                                           SM001090
      F=0.0791*(RE**(-0.25))                                            SM001100
```

FILE: SMOOTHBR FORTRAN A1 ANLVM VM/SP 405 CMS

```
      FS=0.0791*(RES**(-0.25))
      WRITE(6,9) RE,F,RHOBAR,RES,FS,RHOA
      WRITE(50,9) RE,F,RHOBAR,RES,FS,RHOA
9     FORMAT(1X,'REYNOLDS=',F10.2,5X,'FRIC. FACTOR=',F10.6,5X,'RHOBAR='
     >,F10.3,/,1X,'REYN STACK=',F10.2,5X,'FRIC F STACK=',F10.6,1X,'DEN
     >STACK=',F10.3)
      DELPH=F*(G**2)*LH*(TA/T0+1.0)/(DH*RHO)
      DELPS=(2.0*FS*(G**2)*LS/(RHOA*DHS))*((AFH/AFS)**2)
      DPACL=(TA/T0-1.0)*(G**2)/RHO
      DPKLOS=KLOSS*(G**2)*RHOI/2.0
      DPLOST=DELPH+DELPS+DPACL+DPKLOS
      DPHEAD=RHO*GRAV*((1.0-RHOBAR/RHO)*LH+(1.0-RHOA/RHO)*LS)
      DPERR=DPHEAD-DPLOST
      PR=NU/ALPHA
C     DITTUS-BOELTER CORRELATION FOR HW
      HW=(0.023*(RE**0.8))*(PR**0.4)*K/DH
C     CORRELATION FOR HW DERIVED FROM IDS TEST
C     HW=(1.22*(RE**0.457))*(0.72**0.4)*K/DH
C     WESTINGHOUSE PETUHKOV CORRELATION FOR HW
C     F2=1./((1.82*ALOG10(RE)-1.64)**2)
C     HNUM=RE*PR*F2/8.
C     HDEN1=PR**(2./3.)-1.
C     HDEN2=12.7*((F2/8.)**0.5)
C     HW=(HNUM/(1.07+HDEN2*HDEN1))*K/DH
      HD=HW
      BW=QW/(G*CP*H)
      BS=BW
10    AS=T0+(QW-HW*(AW-T0))/HD
      TERM4=(AW+BW*LH/2.)**4
      TERM5=(AS+BS*LH/2.)**4
      TERM6=HD*(1.0/EPSW+1.0/EPSS-1.0)
      ASNEW=T0+SIGMA*(TERM4-TERM5)/TERM6
      DELAS=ASNEW-AS
      IF(DABS(DELAS).LT.0.001) GO TO 30
      AW=AW-DELAS*CCONV
C     WRITE(6,*) ASNEW,AS,DELAS,AW,BW
      GO TO 10
30    WRITE(6,40) DELAS
40    FORMAT(1X,'ERROR IN CALCULATED VALUE OF AS=',F10.4)
      TA=T0+QW*LH/(G*CP*H)
      UAVE=G/RHOBAR
      TGV=AW+BW*LH
      TFS=AS+BS*LH
      TGVBAR=(AW+TGV)/2.0
      EPSA=1.0/(2.0/EPSRV-1.0)
      TRVBAR=(TGVBAR**4+QW/(SIGMA*EPSA))**0.25
      TGV0=AW
      TRV0=(TGV0**4+QW/(SIGMA*EPSA))**0.25
      HOVRAL=QW/(TRV0-T0)
      TRV0=TRV0*1.8-459.69
      HOVRAL=HOVRAL/5.678263
      WRITE(6,43) TRV0,HOVRAL
      WRITE(50,43) TRV0,HOVRAL
43    FORMAT(1X,'$$$$',5X,'TRV0=',F10.4,5X,'HOVRAL=',F10.4,5X,'$$$$')
      QW=QW*1.E-3
```

FILE: SMOOTHBR FORTRAN A1 ANLVM VM/SP 405 CMS

```
      QW=QW*(0.3048**2)
      WRITE(6,44) QW
      WRITE(50,44) QW
44    FORMAT(1X,'HEAT FLUX-(KW/FT**2)=',F10.4)
      WRITE(6,45)
      WRITE(50,45)
45    FORMAT(5X,'H',10X,'UAVE',10X,'TA',10X,'TGV0',6X,'TGV',8X,'TFS0',
     Y6X,'TFS',6X,'HW',6X,'G')
       BRH=H/0.3048
       UAVE=UAVE/0.3048
       TA=TA*1.8-459.69
       AW=AW*1.8-459.69
       TGV=TGV*1.8-459.69
       TGVBAR=0.5*(AW+TGV)
      TRVBAR=1.8*TRVBAR-459.69
       AS=AS*1.8-459.69
        TFS=TFS*1.8-459.69
       BRHW=HW/5.678263
      G=G/0.435924
      WRITE(50,50) BRH,UAVE,TA,AW,TGV,AS,TFS,BRHW,G
      WRITE(6,50) BRH,UAVE,TA,AW,TGV,AS,TFS,BRHW,G
50    FORMAT(1X,9F10.4,///)
      WRITE(6,54) TRVBAR,TGVBAR
      WRITE(50,54) TRVBAR,TGVBAR
54    FORMAT(1X,'AVERAGE REACTOR VESSEL TEMP.(F)=',F10.4,
     >'AVERAGE GUARD VESSEL TEMP.(F)=',F10.4,/)
      PCONV=6.894747D3
      DELPH=DELPH/PCONV
      DELPS=DELPS/PCONV
      DPACL=DPACL/PCONV
      DPKLOS=DPKLOS/PCONV
      DPLOST=DPLOST/PCONV
      DPHEAD=DPHEAD/PCONV
      DPERR=DPERR/PCONV
      RATIO=DELPH/DPLOST
      BRHIN=12.D0*BRH
      WRITE(60,*) BRHIN, RATIO
      WRITE(6,55) DELPH,DELPS,DPACL,DPKLOS,DPLOST,DPHEAD,DPERR
      WRITE(50,55)DELPH,DELPS,DPACL,DPKLOS,DPLOST,DPHEAD,DPERR
55    FORMAT(1X,'P LOS FRIC-H=',D10.5,2X,'P LOS FRIC-S=',D10.5,2X,
     >'ACCEL LOSS=',D10.5,/,1X,'FORM LOS=',D10.5,2X,'TOTAL P LOS='
     >,D10.5,/,2X, 'TOT HEAD=',D10.5,2X,'HEAD-LOS ERR=',D12.7)
      WRITE(6,56)
      WRITE(50,56)
56    FORMAT(///,1X,'$$$$$$$$$$  END OF CASE  $$$$$$$$$$',///)
      WRITE(6,60)
60    FORMAT(1X,'ENTER POSITIVE NO. TO CHANGE GEOMETRY: NEGATIVE FOR
     >NO CHANGE')
      READ(5,*) IGEOM
      IF(IGEOM.GT.0) GO TO 1
      WRITE(6,65)
65    FORMAT(1X,'ENTER POSITIVE NO. TO CHANGE HEAT FLUX; NEGATIVE
     >TO TERMINATE')
      READ(5,*) IQW
      IF(IQW) 100,100,7
```

FILE: SMOOTHBR FORTRAN A1 ANLVM VM/SP 405 CMS

```
100   STOP                                                        SMO02210
      END                                                         SMO02220
```